CHAPTER 15

NAVIGATIONAL ASTRONOMY

PRELIMINARY CONSIDERATIONS

1500. Definition

Astronomy predicts the future positions and motions of celestial bodies and seeks to understand and explain their physical properties. Navigational astronomy, dealing principally with celestial coordinates, time, and the apparent motions of celestial bodies, is the branch of astronomy most important to the navigator. The symbols commonly recognized in navigational astronomy are given in Table 1500.

Celestial Bodies

☉	Sun	☉̲ ☾̲	Lower limb
☾	Moon	⊖ ☾	Center
☿	Mercury	☉̄ ☾̄	Upper limb
♀	Venus	●	New moon
⊕	Earth	◐	Crescent moon
♂	Mars	◐	First quarter
♃	Jupiter	◐	Gibbous moon
♄	Saturn	○	Full moon
⛢	Uranus	◑	Gibbous moon
♆	Neptune	◑	Last quarter
♇	Pluto	◑	Crescent moon
☆	Star		
☆-P	Star-planet altitude correction (altitude)		

Miscellaneous Symbols

y	Years	✳	Interpolation impractical
m	Months	°	Degrees
d	Days	′	Minutes of arc
h	Hours	″	Seconds of arc
m	Minutes of time	☌	Conjunction
s	Seconds of time	☍	Opposition
▬	Remains below horizon	□	Quadrature
▭	Remains above horizon	☊	Ascending node
////	Twilight all night	☋	Descending node

Signs of the Zodiac

♈	Aries (vernal equinox)	♎	Libra (autumnal equinox)
♉	Taurus	♏	Scorpius
♊	Gemini	♐	Sagittarius
♋	Cancer (summer solstice)	♑	Capricornus (winter solstice)
♌	Leo	♒	Aquarius
♍	Virgo	♓	Pisces

Table 1500. Astronomical symbols.

1501. The Celestial Sphere

Looking at the sky on a dark night, imagine that celestial bodies are located on the inner surface of a vast, earth-centered sphere. This model is useful since we are only interested in the relative positions and motions of celestial bodies on this imaginary surface. Understanding the concept of the celestial sphere is most important when discussing sight reduction in Chapter 20.

1502. Relative And Apparent Motion

Celestial bodies are in constant motion. There is no fixed position in space from which one can observe absolute motion. Since all motion is relative, the position of the observer must be noted when discussing planetary motion. From the earth we see apparent motions of celestial bodies on the celestial sphere. In considering how planets follow their orbits around the sun, we assume a hypothetical observer at some distant point in space. When discussing the rising or setting of a body on a local horizon, we must locate the observer at a particular point on the earth because the setting sun for one observer may be the rising sun for another.

Motion on the celestial sphere results from the motions in space of both the celestial body and the earth. Without special instruments, motions toward and away from the earth cannot be discerned.

1503. Astronomical Distances

Consider the celestial sphere as having an infinite radius because distances between celestial bodies are remarkably vast. The difficulty of illustrating astronomical distances is indicated by the fact that if the earth were represented by a circle one inch in diameter, the moon would be a circle one-fourth inch in diameter at a distance of 30 inches, the sun would be a circle nine feet in diameter at

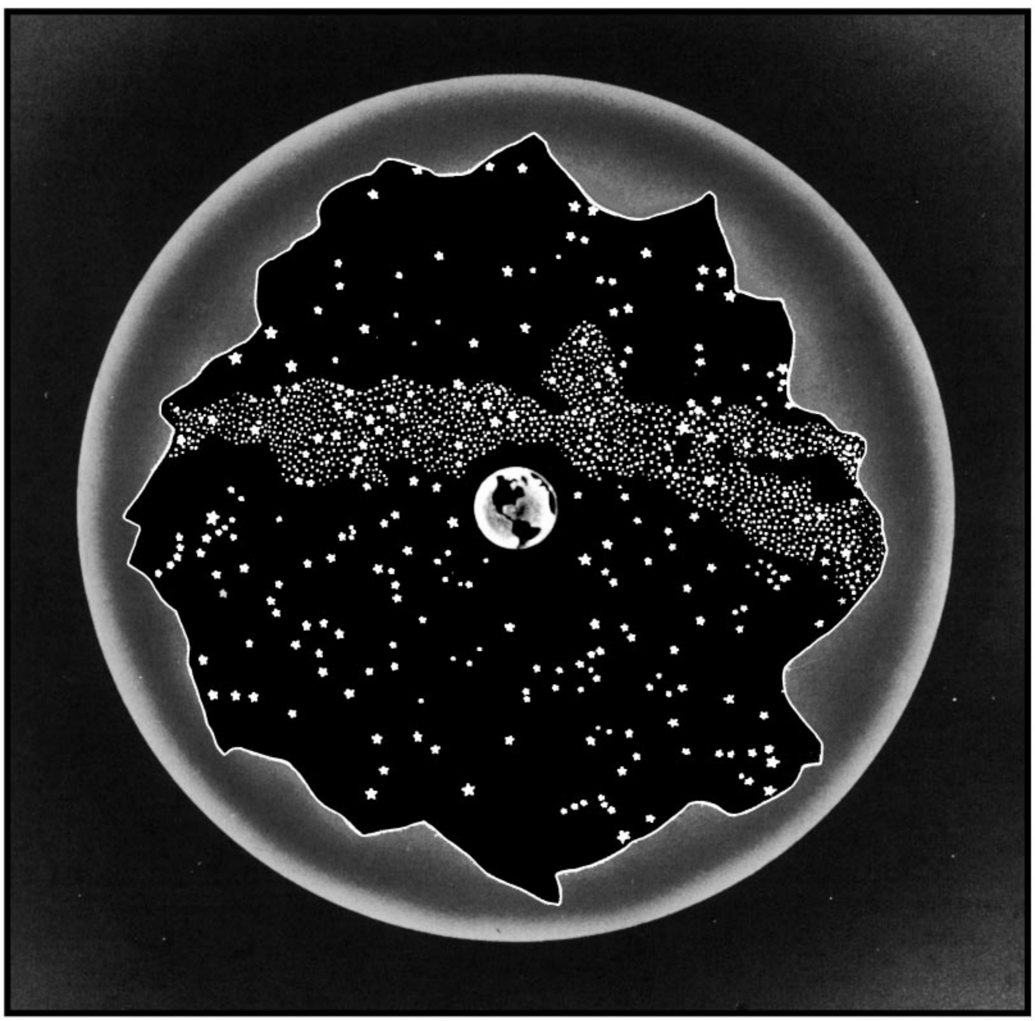


Figure 1501. The celestial sphere.

a distance of nearly a fifth of a mile, and Pluto would be a circle half an inch in diameter at a distance of about seven miles. The nearest star would be one-fifth the actual distance to the moon.

Because of the size of celestial distances, it is inconvenient to measure them in common units such as the mile or kilometer. The mean distance to our nearest neighbor, the moon, is 238,900 miles. For convenience this distance is sometimes expressed in units of the equatorial radius of the earth: 60.27 earth radii.

Distances between the planets are usually expressed in terms of the **astronomical unit (AU)**, the mean distance between the earth and the sun. This is approximately 92,960,000 miles. Thus the mean distance of the earth from the sun is 1 A.U. The mean distance of Pluto, the outermost known planet in our solar system, is 39.5 A.U. Expressed in astronomical units, the mean distance from the earth to the moon is 0.00257 A.U.

Distances to the stars require another leap in units. A commonly-used unit is the **light-year**, the distance light travels in one year. Since the speed of light is about 1.86×10^5 miles per second and there are about 3.16×10^7 seconds per year, the length of one light-year is about 5.88×10^{12} miles. The nearest stars, Alpha Centauri and its neighbor Proxima, are 4.3 light-years away. Relatively few stars are less than 100 light-years away. The nearest galaxies, the Clouds of Magellan, are 150,000 to 200,000 light years away. The most distant galaxies observed by astronomers are several billion light years away.

1504. Magnitude

The relative brightness of celestial bodies is indicated by a scale of stellar **magnitudes**. Initially, astronomers divided the stars into 6 groups according to brightness. The 20 brightest were classified as of the first magnitude, and the dimmest were of the sixth magnitude. In modern times, when it became desirable to define more precisely the limits of magnitude, a first magnitude star was considered 100 times brighter than one of the sixth magnitude. Since the fifth root of 100 is 2.512, this number is considered the **magnitude ratio**. A first magnitude star is 2.512 times as bright as a second magnitude star, which is 2.512 times as bright as a third magnitude star,. A second magnitude is $2.512 \times 2.512 = 6.310$ times as bright as a fourth magnitude star. A first magnitude star is 2.512^{20} times as bright as a star of the 21st magnitude, the dimmest that can be seen through a 200-inch telescope.

Brightness is normally tabulated to the nearest 0.1 magnitude, about the smallest change that can be detected by the unaided eye of a trained observer. All stars of magnitude 1.50 or brighter are popularly called “first magnitude” stars. Those between 1.51 and 2.50 are called “second magnitude” stars, those between 2.51 and 3.50 are called “third magnitude” stars, etc. Sirius, the brightest star, has a magnitude of –1.6. The only other star with a negative magnitude is Canopus, –0.9. At greatest brilliance Venus has a magnitude of about –4.4. Mars, Jupiter, and Saturn are sometimes of negative magnitude. The full moon has a magnitude of about –12.6, but varies somewhat. The magnitude of the sun is about –26.7.

THE UNIVERSE

1505. The Solar System

The **sun**, the most conspicuous celestial object in the sky, is the central body of the solar system. Associated with it are at least nine principal **planets** and thousands of asteroids, comets, and meteors. Some planets like earth have satellites.

1506. Motions Of Bodies Of The Solar System

Astronomers distinguish between two principal motions of celestial bodies. **Rotation** is a spinning motion about an axis within the body, whereas **revolution** is the motion of a body in its orbit around another body. The body around which a celestial object revolves is known as that body’s **primary**. For the satellites, the primary is a planet. For the planets and other bodies of the solar system, the primary is the sun. The entire solar system is held together by the gravitational force of the sun. The whole system revolves around the center of the Milky Way galaxy (section 1515), and the Milky Way is in motion relative to its neighboring galaxies.

The hierarchies of motions in the universe are caused by the force of gravity. As a result of gravity, bodies attract each other in proportion to their masses and to the inverse square of the distances between them. This force causes the planets to go around the sun in nearly circular, elliptical orbits.

In each planet’s orbit, the point nearest the sun is called the **perihelion**. The point farthest from the sun is called the **aphelion**. The line joining perihelion and aphelion is called the **line of apsides**. In the orbit of the moon, the point nearest the earth is called the **perigee**, and that point farthest from the earth is called the **apogee**. Figure 1506 shows the orbit of the earth (with exaggerated eccentricity), and the orbit of the moon around the earth.

1507. The Sun

The sun dominates our solar system. Its mass is nearly a thousand times that of all other bodies of the solar system combined. Its diameter is about 866,000 miles. Since it is a star, it generates its own energy through thermonuclear reactions, thereby providing heat and light for the entire solar system.

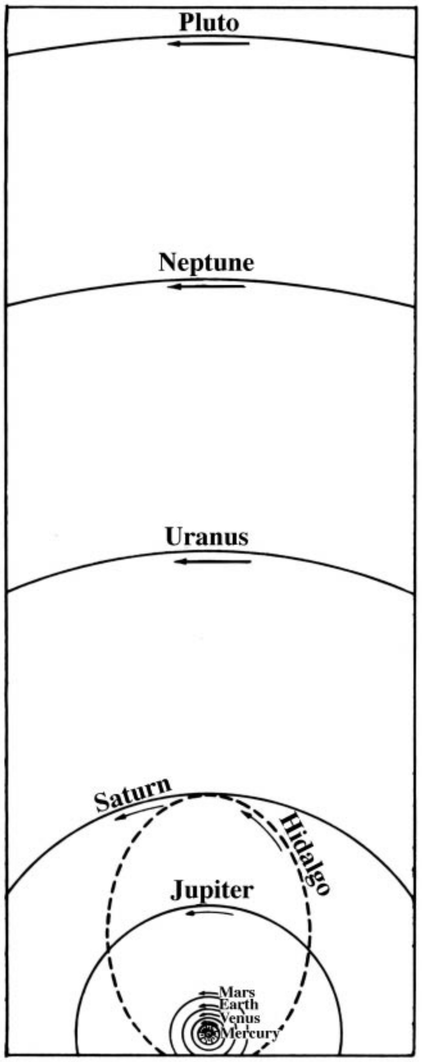


Figure 1505. Relative size of planetary orbits.

The distance from the earth to the sun varies from 91,300,000 at perihelion to 94,500,000 miles at aphelion. When the earth is at perihelion, which always occurs early in January, the sun appears largest, 32.6' in diameter. Six months later at aphelion, the sun's apparent diameter is a minimum of 31.5'.

Observations of the sun's surface (called the **photosphere**) reveal small dark areas called **sunspots**. These are areas of intense magnetic fields in which relatively cool gas (at 7000°F.) appears dark in contrast to the surrounding hotter gas (10,000°F.). Sunspots vary in size from perhaps 50,000 miles in diameter to the smallest spots that can be detected (a few hundred miles in diameter). They generally appear in groups. Large sunspots can be seen without a telescope if the eyes are protected, as by the shade glasses of a sextant.

Surrounding the photosphere is an outer **corona** of very hot but tenuous gas. This can only be seen during an eclipse of the sun, when the moon blocks the light of the photosphere.

The sun is continuously emitting charged particles, which form the **solar wind**. As the solar wind sweeps past the earth, these particles interact with the earth's magnetic field. If the solar wind is particularly strong, the interaction can produce magnetic storms which adversely affect radio signals on the earth. At such times the auroras are particularly brilliant and widespread.

The sun is moving approximately in the direction of Vega at about 12 miles per second, or about two-thirds as fast as the earth moves in its orbit around the sun. This is in addition to the general motion of the sun around the center of our galaxy.

1508. Planets

The principal bodies orbiting the sun are called **planets**. Nine principal planets are known: Mercury, Venus, Earth,

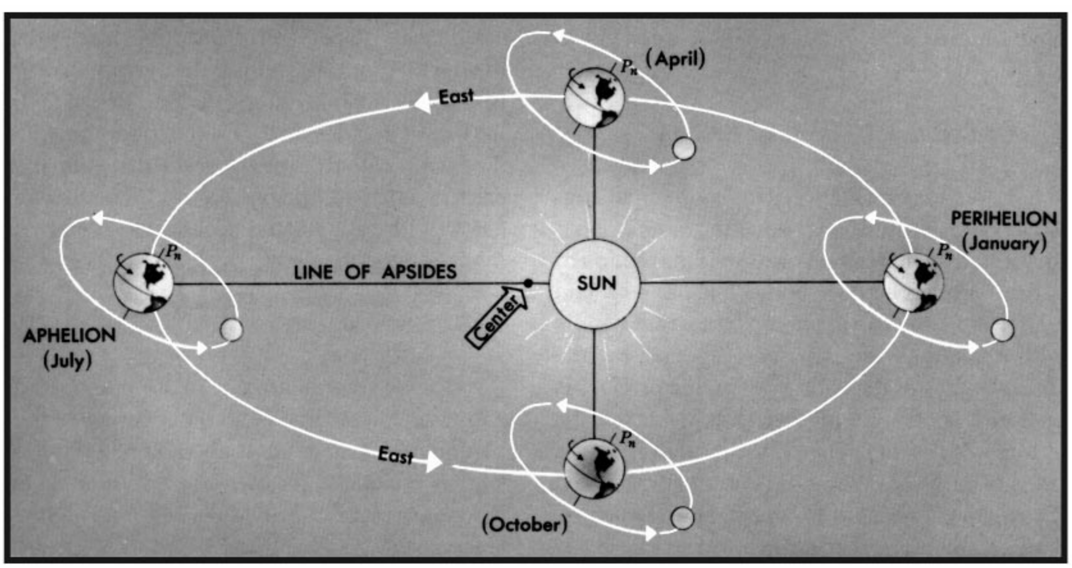


Figure 1506. Orbits of the earth and moon.

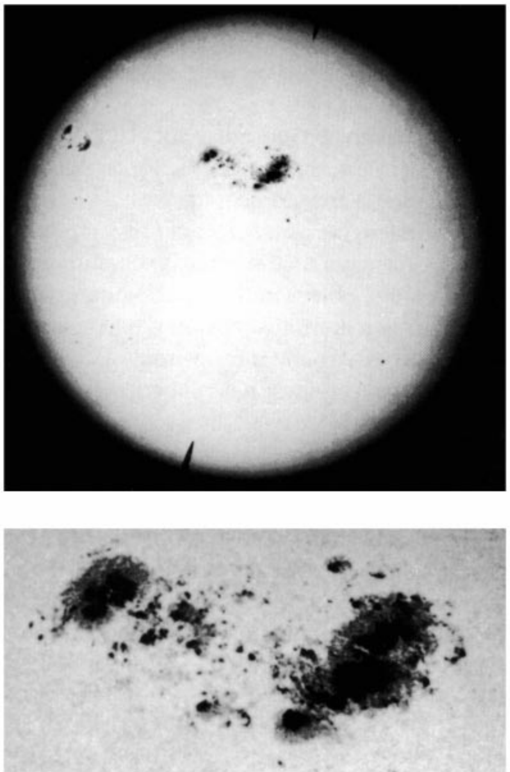


Figure 1507. Whole solar disk and an enlargement of the great spot group of April 7, 1947.
Courtesy of Mt. Wilson and Palomar Observatories.

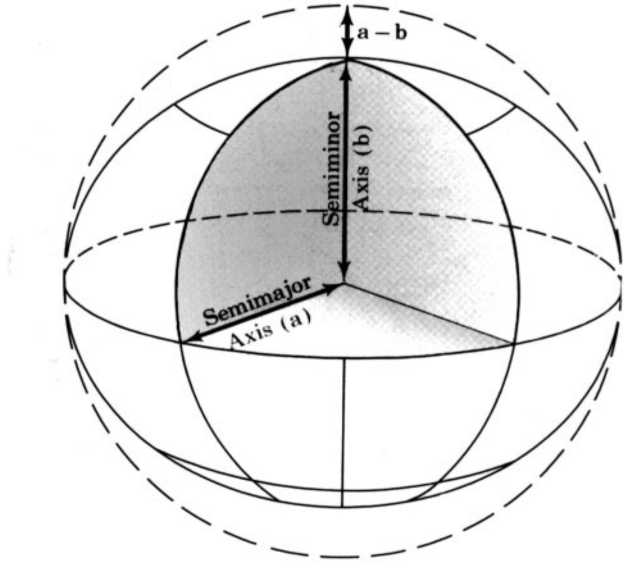


Figure 1509. Oblate spheroid or ellipsoid of revolution.

Figure 1508a

Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Of these, only four are commonly used for celestial navigation: Venus, Mars, Jupiter, and Saturn.

Except for Pluto, the orbits of the planets lie in nearly the same plane as the earth's orbit. Therefore, as seen from the earth, the planets are confined to a strip of the celestial sphere called the **ecliptic**.

The two planets with orbits smaller than that of the earth are called **inferior planets**, and those with orbits larger than that of the earth are called **superior planets**. The four planets nearest the sun are sometimes called the inner planets, and the others the outer planets. Jupiter, Saturn, Uranus, and Neptune are so much larger than the others that they are sometimes classed as major planets. Uranus is barely visible to the unaided eye; Neptune and Pluto are not visible without a telescope.

Planets can be identified in the sky because, unlike the stars, they do not twinkle. The stars are so distant that they are virtually point sources of light. Therefore the tiny stream of light from a star is easily scattered by normal motions of air in the atmosphere causing the affect of twinkling. The naked-eye planets, however, are close enough to present perceptible disks. The broader stream of light from a planet is not easily disrupted unless the planet is low on the horizon or the air is especially turbulent.

The orbits of many thousands of tiny minor planets or asteroids lie chiefly between the orbits of Mars and Jupiter. These are all too faint to be seen with the naked eye.

1509. The Earth

In common with other planets, the earth **rotates** on its axis and **revolves** in its orbit around the sun. These motions are the principal source of the daily apparent motions of other celestial bodies. The earth's rotation also causes a deflection of water and air currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Because of the earth's rotation, high tides on the open sea lag behind the meridian transit of the moon.

For most navigational purposes, the earth can be considered a sphere. However, like the other planets, the earth is approximately an **oblate spheroid**, or **ellipsoid of revolution**, flattened at the poles and bulged at the equator. See Figure 1509. Therefore, the polar diameter is less than the equatorial diameter, and the meridians are slightly elliptical, rather than circular. The dimensions of the earth are recomputed from time to time, as additional and more precise measurements become available. Since the earth is not exactly an ellipsoid, results differ slightly when equally

precise and extensive measurements are made on different parts of the surface.

1510. Inferior Planets

Since Mercury and Venus are inside the earth's orbit, they always appear in the neighborhood of the sun. Over a period of weeks or months, they appear to oscillate back and forth from one side of the sun to the other. They are seen either in the eastern sky before sunrise or in the western sky after sunset. For brief periods they disappear into the sun's glare. At this time they are between the earth and sun (known as **inferior conjunction**) or on the opposite side of the sun from the earth (**superior conjunction**). On rare occasions at inferior conjunction, the planet will cross the face of the sun as seen from the earth. This is known as a **transit of the sun**.

When Mercury or Venus appears most distant from the sun in the evening sky, it is at greatest eastern elongation. (Although the planet is in the western sky, it is at its easternmost point from the sun.) From night to night the planet will approach the sun until it disappears into the glare of twilight. At this time it is moving between the earth and sun to inferior conjunction. A few days later, the planet will appear in the morning sky at dawn. It will gradually move away from the sun to western elongation, then move back toward the sun. After disappearing in the morning twilight, it will move behind the sun to superior conjunction. After this it will reappear in the evening sky, heading toward eastern elongation.

Mercury is never seen more than about 28° from the sun. For this reason it is not commonly used for navigation. Near greatest elongation it appears near the western horizon after sunset, or the eastern horizon before sunrise. At these times it resembles a first magnitude star and is sometimes reported as a new or strange object in the sky. The interval during which it appears as a morning or evening star can vary from about 30 to 50 days. Around inferior conjunction, Mercury disappears for about 5 days; near superior conjunction, it disappears for about 35 days. Observed with a telescope, Mercury is seen to go through phases similar to those of the moon.

Venus can reach a distance of 47° from the sun, allowing it to dominate the morning or evening sky. At maximum brilliance, about five weeks before and after inferior conjunction, it has a magnitude of about –4.4 and is brighter than any other object in the sky except the sun and moon.

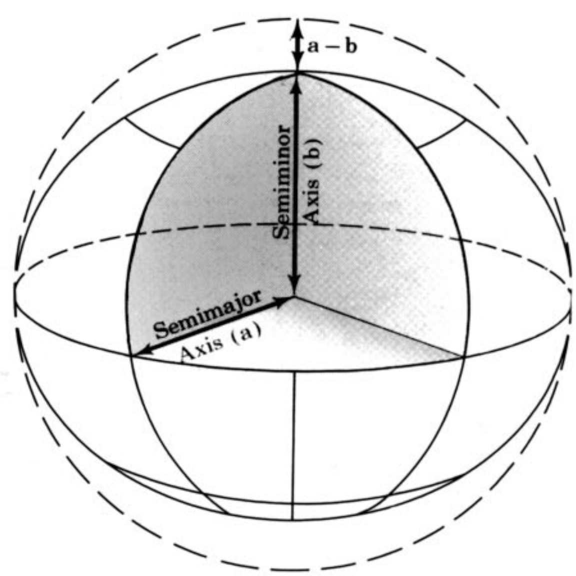


Figure 1510. Planetary configurations.

At these times it can be seen during the day and is sometimes observed for a celestial line of position. It appears as a morning or evening star for approximately 263 days in succession. Near inferior conjunction Venus disappears for 8 days; around superior conjunction it disappears for 50 days. When it transits the sun, Venus can be seen to the naked eye as a

small dot about the size of a group of sunspots. Through binoculars, Venus can be seen to go through a full set of phases.

1511. Superior Planets

As planets outside the earth's orbit, the superior planets are not confined to the proximity of the sun as seen from the earth. They can pass behind the sun (conjunction), but they cannot pass between the sun and the earth. Instead we see them move away from the sun until they are opposite the sun in the sky (**opposition**). When a superior planet is near conjunction, it rises and sets approximately with the sun and is thus lost in the sun's glare. Gradually it becomes visible in the early morning sky before sunrise. From day to day, it rises and sets earlier, becoming increasingly visible through the late night hours until dawn. Approaching opposition, the planet will rise in the late evening, until at opposition, it will rise when the sun sets, be visible throughout the night, and set when the sun rises.

Observed against the background stars, the planets normally move eastward in what is called **direct motion**. Approaching opposition, however, a planet will slow down, pause (at a stationary point), and begin moving westward (**retrograde motion**), until it reaches the next stationary point and resumes its direct motion. This is not because the planet is moving strangely in space. This relative, observed motion results because the faster moving earth is catching up with and passing by the slower moving superior planet.

The superior planets are brightest and closest to the earth at opposition. The interval between oppositions is known as the **synodic period**. This period is longest for the closest planet, Mars, and becomes increasingly shorter for the outer planets.

Unlike Mercury and Venus, the superior planets do not go through a full cycle of phases. They are always full or highly gibbous.

Mars can usually be identified by its orange color. It can become as bright as magnitude –2.8 but is more often between –1.0 and –2.0 at opposition. Oppositions occur at intervals of about 780 days. The planet is visible for about 330 days on either side of opposition. Near conjunction it is lost from view for about 120 days. Its two satellites can only be seen in a large telescope.

Jupiter, largest of the known planets, normally outshines Mars, regularly reaching magnitude –2.0 or brighter at opposition. Oppositions occur at intervals of about 400 days, with the planet being visible for about 180 days before and after opposition. The planet disappears for about 32 days at conjunction. Four satellites (of a total 16 currently known) are bright enough to be seen in binoculars. Their motions around Jupiter can be observed over the course of several hours.

Saturn, the outermost of the navigational planets, comes to opposition at intervals of about 380 days. It is visible for about 175 days before and after opposition, and disappears for about 25 days near conjunction. At opposition it becomes as bright as magnitude +0.8 to –0.2. Through good, high powered binoculars, Saturn appears as elongated because of its system of rings. A telescope is needed to examine the rings in any detail. Saturn is now known to have at least 18 satellites, none of which are visible to the unaided eye.

Uranus, **Neptune** and **Pluto** are too faint to be used for navigation; Uranus, at about magnitude 5.5, is faintly visible to the unaided eye.

1512. The Moon

The **moon** is the only satellite of direct navigational interest. It revolves around the earth once in about 27.3 days, as measured with respect to the stars. This is called the **sidereal month**. Because the moon rotates on its axis with the same period with which it revolves around the earth, the same side of the moon is always turned toward the earth. The cycle of phases depends on the moon's revolution with respect to the sun. This synodic month is approximately 29.53 days, but can vary from this average by up to a quarter of a day during any given month.

When the moon is in conjunction with the sun (new moon), it rises and sets with the sun and is lost in the sun's glare. The moon is always moving eastward at about 12.2° per day, so that sometime after conjunction (as little as 16 hours, or as long as two days), the thin lunar crescent can be observed after sunset, low in the west. For the next couple of weeks, the moon will **wax**, becoming more fully illuminated. From day to day, the moon will rise (and set) later, becoming increasingly visible in the evening sky, until (about 7 days after new moon) it reaches first quarter, when the moon rises about noon and sets about midnight. Over the next week the moon will rise later and later in the afternoon until full moon, when it rises about sunset and dominates the sky throughout the night. During the next couple of weeks the moon will **wane**, rising later and later at night. By last quarter (a week after full moon), the moon rises about midnight and sets at noon. As it approaches new moon, the moon becomes an increasingly thin crescent, and is seen only in the early morning sky. Sometime before conjunction (16 hours to 2 days before conjunction) the thin crescent will disappear in the glare of morning twilight.

At full moon, the sun and moon are on opposite sides of the ecliptic. Therefore, in the winter the full moon rises early, crosses the celestial meridian high in the sky, and sets late; as the sun does in the summer. In the summer the full moon rises in the southeastern part of the sky (Northern Hemisphere), remains relatively low in the sky, and sets along the southwestern horizon after a short time above the horizon.

At the time of the autumnal equinox, the part of the ecliptic opposite the sun is most nearly parallel to the horizon. Since the eastward motion of the moon is approximately along the ecliptic, the delay in the time of rising of the full moon from night to night is less than at other times of the year. The full moon nearest the autumnal equinox is called the **harvest moon**; the full moon a month later is called the **hunter's moon**. See Figure 1512.

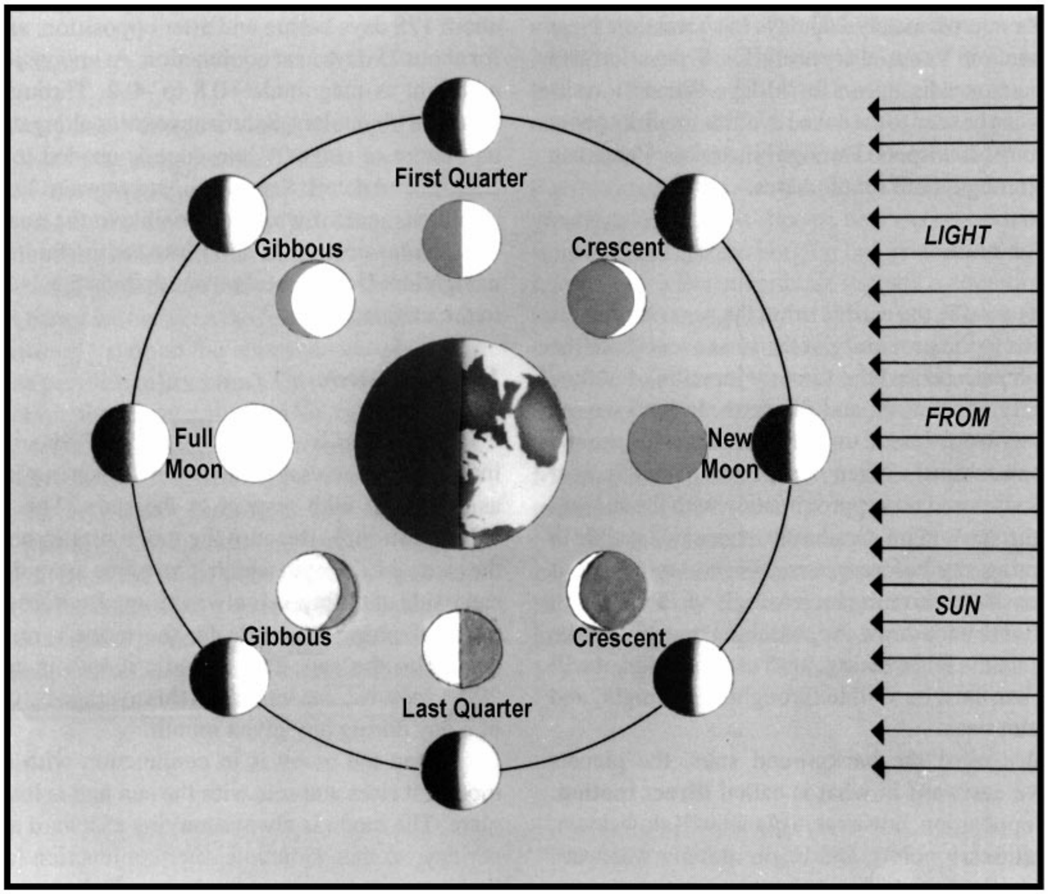


Figure 1512. Phases of the moon. The inner figures of the moon represent its appearance from the earth.

1513. Comets And Meteors

Although **comets** are noted as great spectacles of nature, very few are visible without a telescope. Those that become widely visible do so because they develop long, glowing tails. Comets are swarms of relatively small solid bodies held together by gravity. Around the nucleus, a gaseous head or coma and tail may form as the comet approaches the sun. The tail is directed away from the sun, so that it follows the head while the comet is approaching the sun, and precedes the head while the comet is receding. The total mass of a comet is very small, and the tail is so thin that stars can easily be seen through it. In 1910, the earth passed through the tail of Halley's comet without noticeable effect.

Compared to the well-ordered orbits of the planets, comets are erratic and inconsistent. Some travel east to west and some west to east, in highly eccentric orbits inclined at any angle to the ecliptic. Periods of revolution range from about 3 years to thousands of years. Some comets may speed away from the solar system after gaining velocity as they pass by Jupiter or Saturn.

The short-period comets long ago lost the gasses needed to form a tail. Long period comets, such as Halley's comet, are more likely to develop tails. The visibility of a comet depends very much on how close it approaches the earth. In 1910, Halley's comet spread across the sky. Yet when it returned in 1986, the earth was not well situated to get a good view, and it was barely visible to the unaided eye.

Meteors, popularly called **shooting stars**, are tiny, solid bodies too small to be seen until heated to incandescence by air friction while passing through the earth's atmosphere. A particularly bright meteor is called a **fireball**. One that explodes is called a **bolide**. A meteor that survives its trip through the atmosphere and lands as a solid particle is called a **meteorite**.

Vast numbers of meteors exist. It has been estimated that an average of about 1,000,000 bright enough to be seen enter the earth's atmosphere each hour, and many times this number undoubtedly enter, but are too small to attract attention.

Meteor showers occur at certain times of the year when the earth passes through **meteor swarms**, the scattered remains of comets that have broken up. At these times the number of meteors observed is many times the usual number.

A faint glow sometimes observed extending upward approximately along the ecliptic before sunrise and after sunset has been attributed to the reflection of sunlight from

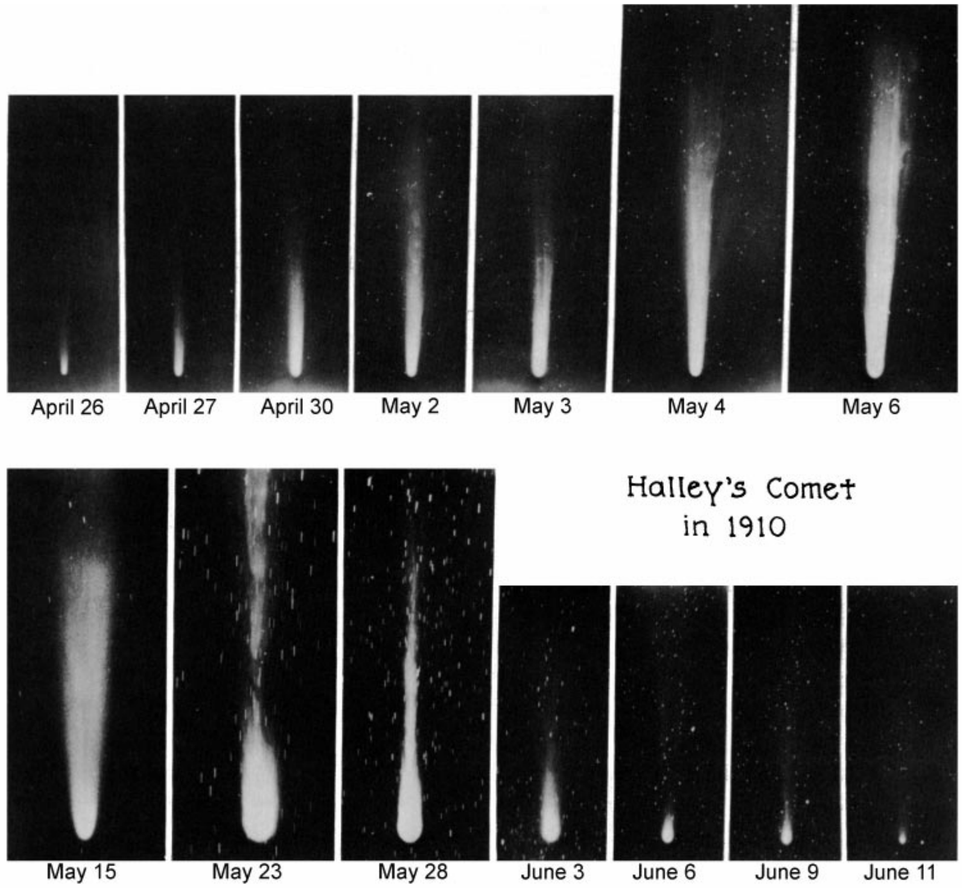


Figure 1513. Halley's Comet; fourteen views, made between April 26 and June 11, 1910.
Courtesy of Mt. Wilson and Palomar Observatories.

quantities of this material. This glow is called **zodiacal light**. A faint glow at that point of the ecliptic 180° from the sun is called the **gegenschein** or **counterglow**.

1514. Stars

Stars are distant suns, in many ways resembling the body which provides the earth with most of its light and heat. Like the sun, stars are massive balls of gas that create their own energy through thermonuclear reactions.

Although stars differ in size and temperature, these differences are apparent only through analysis by astronomers. Some differences in color are noticeable to the unaided eye. While most stars appear white, some (those of lower temperature) have a reddish hue. In Orion, blue Rigel and red Betelgeuse, located on opposite sides of the belt, constitute a noticeable contrast.

The stars are not distributed uniformly around the sky. Striking configurations, known as **constellations**, were noted by ancient peoples, who supplied them with names and myths. Today astronomers use constellations—88 in all—to identify areas of the sky.

Under ideal viewing conditions, the dimmest star that can be seen with the unaided eye is of the sixth magnitude. In the entire sky there are about 6,000 stars of this magnitude or brighter. Half of these are below the horizon at any time. Because of the greater absorption of light near the horizon, where the path of a ray travels for a greater distance through the atmosphere, not more than perhaps 2,500 stars are visible to the unaided eye at any time. However, the average navigator seldom uses more than perhaps 20 or 30 of the brighter stars.

Stars which exhibit a noticeable change of magnitude are called **variable stars**. A star which suddenly becomes several magnitudes brighter and then gradually fades is called a **nova**. A particularly bright nova is called a **supernova**.

Two stars which appear to be very close together are called a **double star**. If more than two stars are included in the group, it is called a **multiple star**. A group of a few dozen to several hundred stars moving through space together is called an **open cluster**. The Pleiades is an example of an open cluster. There are also spherically symmetric clusters of hundreds of thousands of stars known as **globular clusters**. The globular clusters are all too distant to be seen with the naked eye.

A cloudy patch of matter in the heavens is called a **nebula**. If it is within the galaxy of which the sun is a part, it is called a **galactic nebula**; if outside, it is called an **extragalactic nebula**.

Motion of a star through space can be classified by its vector components. That component in the line of sight is called **radial motion**, while that component across the line of sight, causing a star to change its apparent position relative to the background of more distant stars, is called **proper motion**.

1515. Galaxies

A **galaxy** is a vast collection of clusters of stars and clouds of gas. The earth is located in the Milky Way galaxy, a slowly spinning disk more than 100,000 light years in diameter. All the bright stars in the sky are in the Milky Way. However, the most dense portions of the galaxy are seen as the great, broad band that glows in the summer nighttime sky. When we look toward the constellation Sagittarius, we are looking toward the center of the Milky Way, 30,000 light years away.

Despite their size and luminance, almost all other galaxies are too far away to be seen with the unaided eye. An exception in the northern hemisphere is the Great Galaxy (sometimes called the Great Nebula) in Andromeda, which appears as a faint glow. In the southern hemisphere, the Large and Small Magellanic Clouds (named after Ferdinand Magellan) are the nearest known neighbors of the Milky Way. They are approximately 1,700,000 light years distant. The Magellanic Clouds can be seen as sizable glowing patches in the southern sky.

Figure 1515. Spiral nebula Messier 51, In Canes Venetici. Satellite nebula is NGC 5195.
Courtesy of Mt. Wilson and Palomar Observatories.

APPARENT MOTION

1516. Apparent Motion Due To Rotation Of The Earth

Apparent motion caused by the earth's rotation is much greater than any other observed motion of celestial bodies. It is this motion that causes celestial bodies to appear to rise along the eastern half of the horizon, climb to maximum altitude as they cross the meridian, and set along the western horizon, at about the same point relative to due west as the rising point was to due east. This apparent motion along the daily path, or **diurnal circle**, of the body is approximately parallel to the plane of the equator. It would be exactly so if rotation of the earth were the only motion and the axis of rotation of the earth were stationary in space.

The apparent effect due to rotation of the earth varies with the latitude of the observer. At the equator, where the equatorial plane is vertical (since the axis of rotation of the earth is parallel to the plane of the horizon), bodies appear to rise and set vertically. Every celestial body is above the horizon approximately half the time. The celestial sphere as seen by an observer at the equator is called the right sphere, shown in Figure 1516a.

For an observer at one of the poles, bodies having constant declination neither rise nor set (neglecting precession of the equinoxes and changes in refraction), but circle the sky, always at the same altitude, making one complete trip around the horizon each day. At the North Pole the motion is clockwise, and at the South Pole it is counterclockwise. Approximately half the stars are always above the horizon and the other half never are. The parallel sphere at the poles is illustrated in Figure 1516b.

Between these two extremes, the apparent motion is a combination of the two. On this oblique sphere, illustrated in Figure 1516c, circumpolar celestial bodies remain above the horizon during the entire 24 hours, circling the elevated celestial pole each day. The stars of Ursa Major (the Big Dipper) and Cassiopeia are circumpolar for many observers in the United States. An approximately equal part of the celestial sphere remains below the horizon during the entire day. Crux is not visible to most observers in the United States. Other bodies rise obliquely along the eastern horizon, climb to maximum altitude at the celestial meridian, and set along the western horizon. The length of time above the horizon and the altitude at meridian transit vary with both the latitude of

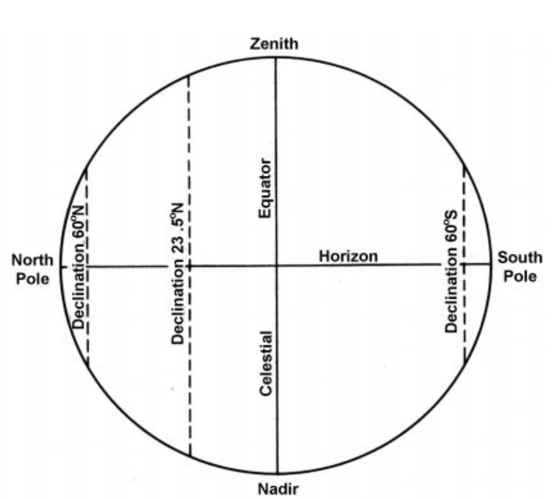


Figure 1516a. The right sphere.

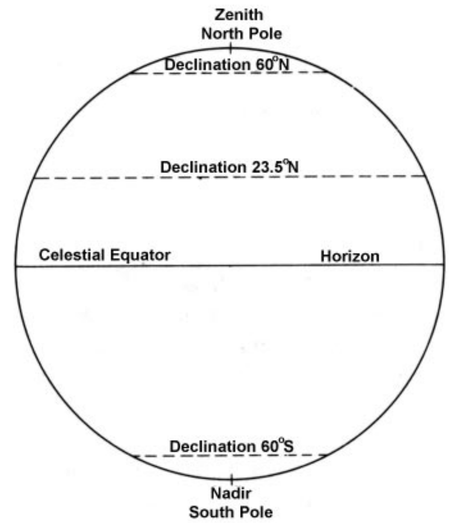


Figure 1516b. The parallel sphere.

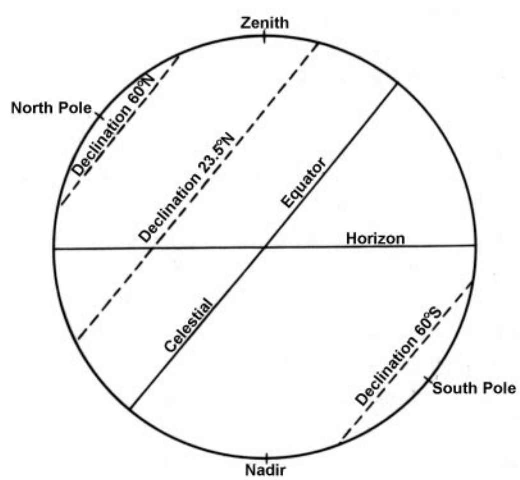


Figure 1516c. The oblique sphere at latitude 40°N.

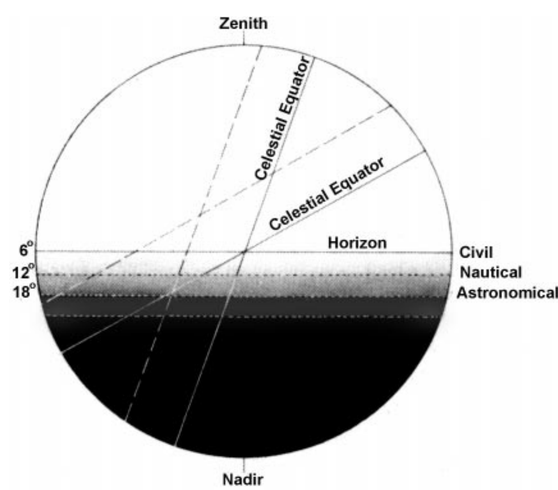


Figure 1516d. The various twilight at latitude 20°N and latitude 60°N.

the observer and the declination of the body. At the polar circles of the earth even the sun becomes circumpolar. This is the land of the midnight sun, where the sun does not set during part of the summer and does not rise during part of the winter.

The increased obliquity at higher latitudes explains why days and nights are always about the same length in the tropics, and the change of length of the day becomes greater as the latitude increases. It also explains why twilight lasts longer in higher latitudes. Twilight is the period of incomplete darkness following sunset and preceding sunrise. Evening twilight starts at sunset, and morning twilight ends at sunrise. The darker limit of twilight occurs when the center of the sun is a stated number of degrees below the celestial horizon. Three kinds of twilight are defined: civil, nautical and astronomical.

Twilight	*Lighter limit*	*Darker limit*	*At darker limit*
civil	–0°50'	–6°	Horizon clear; bright stars visible
nautical	–0°50'	–12°	Horizon not visible
astronomical	–0°50'	–18°	Full night

The conditions at the darker limit are relative and vary considerably under different atmospheric conditions

In Figure 1516d, the twilight band is shown, with the darker limits of the various kinds indicated. The nearly vertical celestial equator line is for an observer at latitude 20°N. The nearly horizontal celestial equator line is for an observer at latitude 60°N. The broken line in each case is the diurnal circle of the sun when its declination is 15°N. The relative duration of any kind of twilight at the two latitudes is indicated by the portion of the diurnal circle between the horizon and the darker limit, although it is not directly proportional to the relative length of line shown since the projection is orthographic. The duration of twilight at the higher latitude is longer, proportionally, than shown. Note that complete darkness does not occur at latitude 60°N when the declination of the sun is 15°N.

1517. Apparent Motion Due To Revolution Of The Earth

If it were possible to stop the rotation of the earth so that the celestial sphere would appear stationary, the effects of the revolution of the earth would become more noticeable. In one year the sun would appear to make one complete trip around the earth, from west to east. Hence, it would seem to move eastward a little less than 1° per day. This motion can be observed by watching the changing position of the sun among the stars. But since both sun and stars generally are not visible at the same time, a better way is to observe the constellations at the same time each night. On any night a star rises nearly four minutes earlier than on the previous night. Thus, the celestial sphere appears to shift westward nearly 1° each night, so that different constellations are associated with different seasons of the year.

Apparent motions of planets and the moon are due to a combination of their motions and those of the earth. If the rotation of the earth were stopped, the combined apparent motion due to the revolutions of the earth and other bodies would be similar to that occurring if both rotation and revolution of the earth were stopped. Stars would appear nearly stationary in the sky but would undergo a small annual cycle of change due to aberration. The motion of the earth in its orbit is sufficiently fast to cause the light from stars to appear to shift slightly in the direction of the earth's motion. This is similar to the effect one experiences when walking in vertically-falling rain that appears to come from ahead due to the observer's own forward motion. The apparent direction of the light ray from the star is the vector difference of the motion of light and the motion of the earth, similar to that of apparent wind on a moving vessel. This effect is most apparent for a body perpendicular to the line of travel of the earth in its orbit, for which it reaches a maximum value of 20.5". The effect of aberration can be noted by comparing the coordinates (declination and sidereal hour angle) of various stars throughout the year. A change is observed in some bodies as the year progresses, but at the end of the year the values have returned almost to what they were at the beginning. The reason they do not return exactly is due to proper motion and precession of the equinoxes. It is also due to nutation, an irregularity in the motion of the earth due to the disturbing effect of other celestial bodies, principally the moon. Polar motion is a slight wobbling of the earth about its axis of rotation and sometimes wandering of the poles. This motion, which does not exceed 40 feet from the mean position, produces slight variation of latitude and longitude of places on the earth.

1518. Apparent Motion Due To Movement Of Other Celestial Bodies

Even if it were possible to stop both the rotation and revolution of the earth, celestial bodies would not appear stationary on the celestial sphere. The moon would make one revolution about the earth each sidereal month, rising in the west and setting in the east. The inferior planets would appear to move eastward and westward relative to the sun, staying within the zodiac. Superior planets would appear to make one revolution around the earth, from west to east, each sidereal period.

Since the sun (and the earth with it) and all other stars are in motion relative to each other, slow apparent motions would result in slight changes in the positions of the stars relative to each other. This space motion is, in fact, observed by telescope. The component of such motion across the line of sight, called proper motion, produces a change in the apparent position of the star. The maximum which has been observed is that of Barnard's Star, which is moving at the rate of 10.3 seconds per year. This is a tenth-magnitude star, not visible to the unaided eye. Of the 57 stars listed on the daily pages of the almanacs, Rigil Kentaurus has the greatest proper motion, about 3.7 seconds per year. Arcturus, with 2.3 seconds per year, has the greatest proper motion of the navigational stars in the Northern Hemisphere. In a few thousand years proper motion will be sufficient to materially alter some familiar configurations of stars, notably Ursa Major.

1519. The Ecliptic

The **ecliptic** is the path the sun appears to take among the stars due to the annual revolution of the earth in its orbit. It is considered a great circle of the celestial sphere, inclined at an angle of about 23°26' to the celestial equator, but undergoing a continuous slight change. This angle is

called the **obliquity of the ecliptic**. This inclination is due to the fact that the axis of rotation of the earth is not perpendicular to its orbit. It is this inclination which causes the sun to appear to move north and south during the year, giving the earth its seasons and changing lengths of periods of daylight.

Refer to Figure 1519a. The earth is at perihelion early in January and at aphelion 6 months later. On or about June 21, about 10 or 11 days before reaching aphelion, the northern part of the earth's axis is tilted toward the sun. The north polar regions are having continuous sunlight; the Northern Hemisphere is having its summer with long, warm days and short nights; the Southern Hemisphere is having winter with short days and long, cold nights; and the south polar region is in continuous darkness. This is the **summer solstice**. Three months later, about September 23, the earth has moved a quarter of the way around the sun, but its axis of rotation still points in about the same direction in space. The sun shines equally on both hemispheres, and days and nights are the same length over the entire world. The sun is setting at the North Pole and rising at the South Pole. The Northern Hemisphere is having its autumn, and the Southern Hemisphere its spring. This is the **autumnal equinox**. In another three months, on or about December 22, the Southern Hemisphere is tilted toward the sun and conditions are the reverse of those six months earlier; the Northern Hemisphere is having its winter, and the Southern Hemisphere its summer. This is the **winter solstice**. Three months later, when both hemispheres again receive equal amounts of sunshine, the Northern Hemisphere is having spring and the Southern Hemisphere autumn, the reverse of conditions six months before. This is the **vernal equinox**.

The word "equinox," meaning "equal nights," is applied because it occurs at the time when days and nights are of approximately equal length all over the earth. The word "solstice," meaning "sun stands still," is applied because the sun stops its apparent northward or southward motion and momentarily "stands still" before it starts in the opposite direction. This action, somewhat analogous to the "stand" of the tide, refers to the motion in a north-south direction only, and not to the daily apparent revolution around the earth. Note that it does not occur when the earth is at perihelion or aphelion. Refer to Figure 1519a. At the time of the vernal equinox, the sun is directly over the equator, crossing from the Southern Hemisphere to the Northern Hemisphere. It rises due east and sets due west, remaining above the horizon for approximately 12 hours. It is not exactly 12 hours because of refraction, semidiameter, and the height of the eye of the observer. These cause it to be above the horizon a little longer than below the horizon. Following the vernal equi-

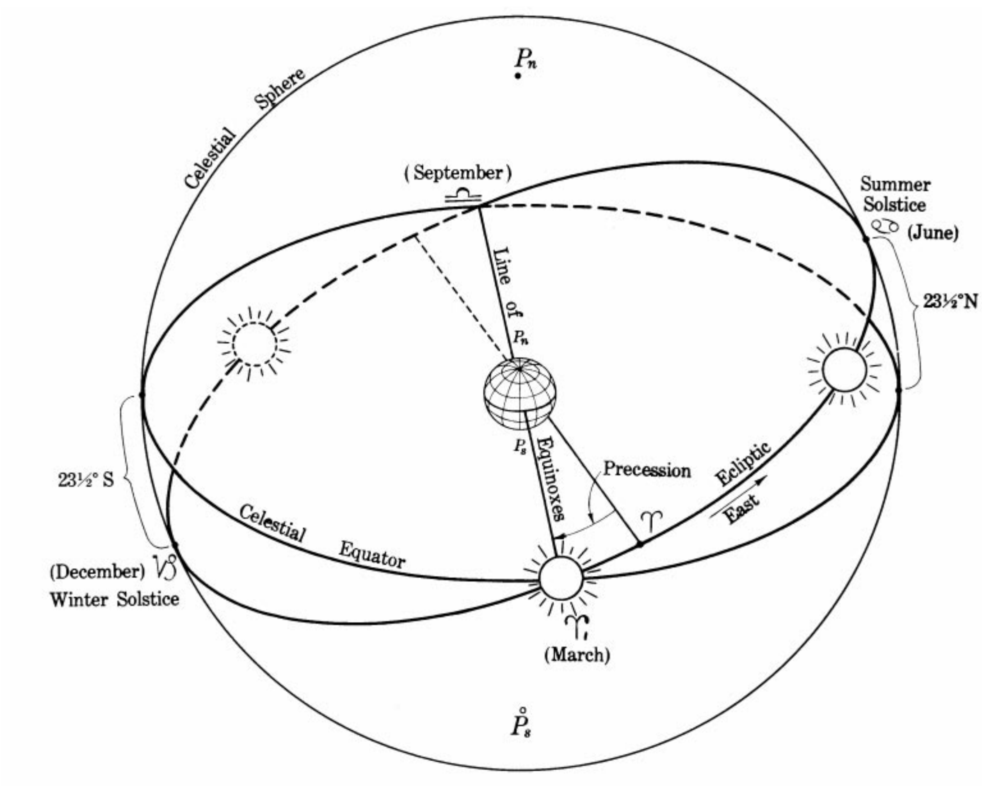


Figure 1519a. Apparent motion of the sun in the ecliptic.

nox, the northerly declination increases, and the sun climbs higher in the sky each day (at the latitudes of the United States), until the summer solstice, when a declination of about 23°26' north of the celestial equator is reached. The sun then gradually retreats southward until it is again over the equator at the autumnal equinox, at about 23°26' south of the celestial equator at the winter solstice, and back over the celestial equator again at the next vernal equinox.

The sun is nearest the earth during the northern hemisphere winter; it is not the distance between the earth and sun that is responsible for the difference in temperature during the different seasons. The reason is to be found in the altitude of the sun in the sky and the length of time it remains above the horizon. During the summer the rays are more nearly vertical, and hence more concentrated, as shown in Figure 1519b. Since the sun is above the horizon more than half the time, heat is being added by absorption during a longer period than it is being lost by radiation. This explains the lag of the seasons. Following the longest day, the earth continues to receive more heat than it dissipates, but at a decreasing proportion. Gradually the proportion decreases until a balance is reached, after which the earth cools, losing more heat than it gains. This is analogous to the day, when the highest temperatures normally occur several hours after the sun reaches maximum altitude at meridian transit. A similar lag occurs at other seasons of the year. Astronomically, the seasons begin at the equinoxes and solstices. Meteorologically, they differ from place to place.

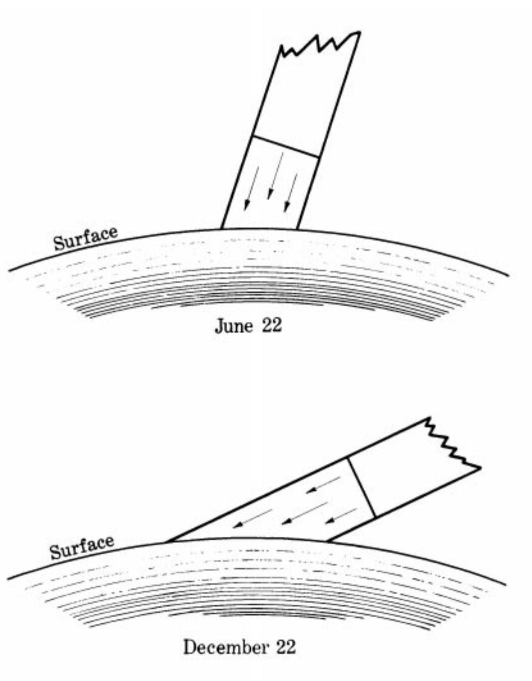


Figure 1519b. Sunlight in summer and winter. Compare the surface covered by the same amount of sunlight on the two dates.

Since the earth travels faster when nearest the sun, the northern hemisphere (astronomical) winter is shorter than its summer by about seven days.

Everywhere between the parallels of about 23°26'N and about 23°26'S the sun is directly overhead at some time during the year. Except at the extremes, this occurs twice: once as the sun appears to move northward, and the second time as it moves southward. This is the **torrid zone**. The northern limit is the **Tropic of Cancer**, and the southern limit's the **Tropic of Capricorn**. These names come from the constellations which the sun entered at the solstices when the names were first applied more than 2,000 years ago. Today, the sun is in the next constellation toward the west because of precession of the equinoxes. The parallels about 23°26' from the poles, marking the approximate limits of the circumpolar sun, are called **polar circles**, the one in the Northern Hemisphere being the **Arctic Circle** and the one in the Southern Hemisphere the **Antarctic Circle**. The areas inside the polar circles are the north and south **frigid zones**. The regions between the frigid zones and the torrid zones are the north and south **temperate zones**.

The expression "vernal equinox" and associated expressions are applied both to the *times* and *points of occurrence* of the various phenomena. Navigationally, the vernal equinox is sometimes called the **first point of Aries** (symbol ♈) because, when the name was given, the sun entered the constellation Aries, the ram, at this time. This point is of interest to navigators because it is the origin for measuring **sidereal hour angle**. The expressions March equinox, June solstice, September equinox, and December solstice are occasionally applied as appropriate, because the more common names are associated with the seasons in the Northern Hemisphere and are six months out of step for the Southern Hemisphere.

The axis of the earth is undergoing a precessional motion similar to that of a top spinning with its axis tilted. In about 25,800 years the axis completes a cycle and returns to the position from which it started. Since the celestial equator is 90° from the celestial poles, it too is moving. The result is a slow westward movement of the equinoxes and solstices, which has already carried them about 30°, or one constellation, along the ecliptic from the positions they occupied when named more than 2,000 years ago. Since sidereal hour angle is measured from the vernal equinox, and declination from the celestial equator, the coordinates of celestial bodies would be changing even if the bodies themselves were stationary. This westward motion of the equinoxes along the ecliptic is called **precession of the equinoxes**. The total amount, called **general precession**, is about 50.27 seconds per year (in 1975). It may be considered divided into two components: precession in right ascension (about 46.10 seconds per year) measured along the celestial equator, and precession in declination (about 20.04" per year) measured perpendicular to the celestial equator. The annual change in the coordinates of any given star, due to precession alone, depends upon its position on the celes-

tial sphere, since these coordinates are measured relative to the polar axis while the precessional motion is relative to the ecliptic axis.

Due to precession of the equinoxes, the celestial poles are slowly describing circles in the sky. The north celestial pole is moving closer to Polaris, which it will pass at a distance of approximately 28 minutes about the year 2102. Following this, the polar distance will increase, and eventually other stars, in their turn, will become the Pole Star.

The precession of the earth's axis is the result of gravitational forces exerted principally by the sun and moon on the earth's equatorial bulge. The spinning earth responds to these forces in the manner of a gyroscope. Regression of the nodes introduces certain irregularities known as nutation in the precessional motion.

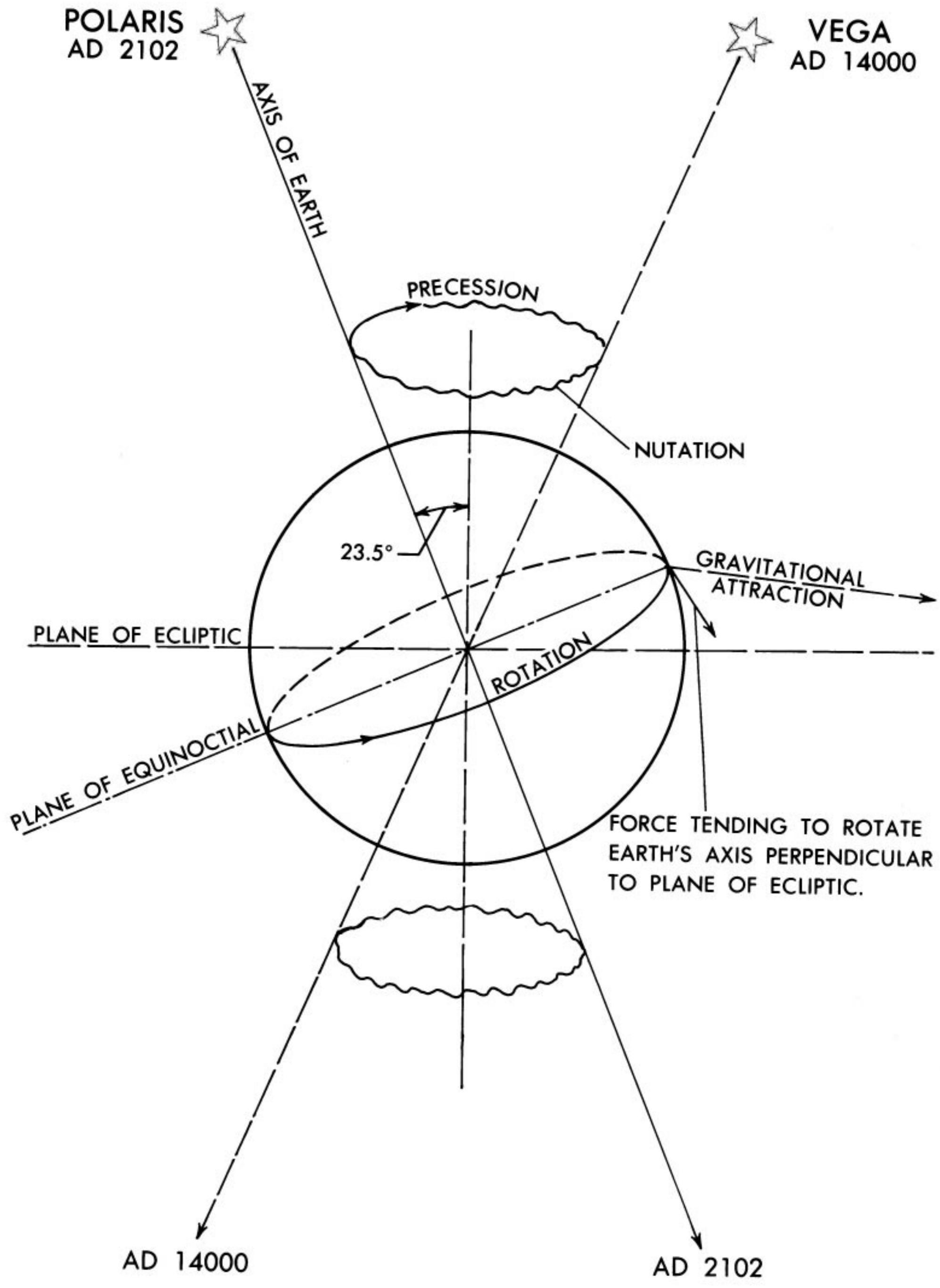


Figure 1519c. Precession and nutation.

1520. The Zodiac

The **zodiac** is a circular band of the sky extending 8° on each side of the ecliptic. The navigational planets and the moon are within these limits. The zodiac is divided into 12 sections of 30° each, each section being given the name and symbol (“sign”) of a constellation. These are shown in Figure 1520. The names were assigned more than 2,000 years ago, when the sun entered Aries at the vernal equinox, Cancer at the summer solstice, Libra at the autumnal equinox, and Capricornus at the winter solstice. Because of precession, the zodiacal signs have shifted with respect to the constellations. Thus at the time of the vernal equinox, the sun is said to be at the “first point of Aries,” though it is in the constellation Pisces. The complete list of signs and names is given below.

1521. Time And The Calendar

Traditionally, astronomy has furnished the basis for measurement of time, a subject of primary importance to the navigator. The **year** is associated with the revolution of the earth in its orbit. The **day** is one rotation of the earth about its axis.

The duration of one rotation of the earth depends upon the external reference point used. One rotation relative to the sun is called a **solar day**. However, rotation relative to the apparent sun (the actual sun that appears in the sky) does not provide time of uniform rate because of variations in the rate of revolution and rotation of the earth. The error due to lack of uniform rate of revolution is removed by using a fictitious **mean sun**. Thus, mean solar time is nearly equal to the average apparent solar time. Because the accumulated difference between these times, called the **equation of time**, is continually changing, the period of daylight is shifting slightly, in addition to its increase or decrease in length due to changing declination. Apparent and mean suns seldom cross the celestial meridian at the same time. The earliest sunset (in latitudes of the United States) occurs about two weeks before the winter solstice, and the latest sunrise occurs about two weeks after winter solstice. A similar but smaller apparent discrepancy occurs at the summer solstice.

Universal Time is a particular case of the measure known in general as mean solar time. Universal Time is the mean solar time on the Greenwich meridian, reckoned in days of 24 mean solar hours beginning with 0 hours at midnight. Universal Time and sidereal time are rigorously related by a formula so that if one is known the other can be found. Universal Time is the standard in the application of astronomy to navigation.

If the vernal equinox is used as the reference, a **sidereal day** is obtained, and from it, **sidereal time**. This indicates the approximate positions of the stars, and for this reason it is the basis of star charts and star finders. Because of the revolution of the earth around the sun, a sidereal day is about 3 minutes 56 seconds shorter than a solar day, and there is one more sidereal than solar days in a year. One

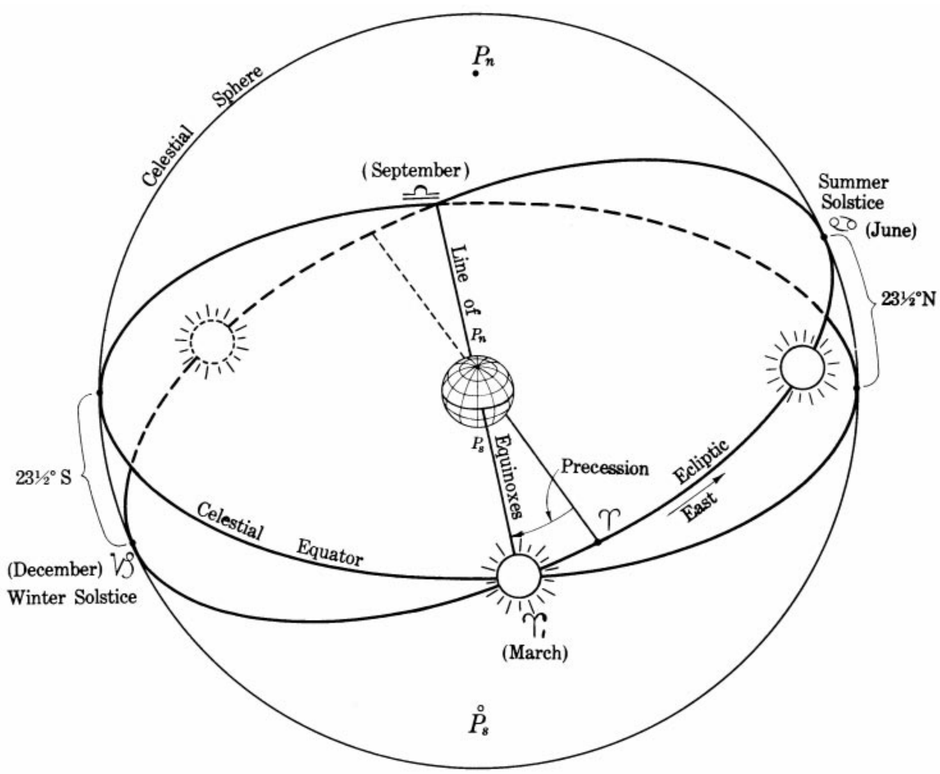


Figure 1520. The zodiac.

mean solar day equals 1.00273791 mean sidereal days. Because of precession of the equinoxes, one rotation of the earth with respect to the stars is not quite the same as one rotation with respect to the vernal equinox. One mean solar day averages 1.0027378118868 rotations of the earth with respect to the stars.

In tide analysis, the moon is sometimes used as the reference, producing a **lunar day** averaging 24 hours 50 minutes (mean solar units) in length, and lunar time.

Since each kind of day is divided arbitrarily into 24 hours, each hour having 60 minutes of 60 seconds, the length of each of these units differs somewhat in the various kinds of time.

Time is also classified according to the terrestrial meridian used as a reference. **Local time** results if one's own meridian is used, **zone time** if a nearby reference meridian is used over a spread of longitudes, and **Greenwich** or **Universal Time** if the Greenwich meridian is used.

The period from one vernal equinox to the next (the cycle of the seasons) is known as the **tropical year**. It is approximately 365 days, 5 hours, 48 minutes, 45 seconds, though the length has been slowly changing for many centuries. Our calendar, the Gregorian calendar, approximates the tropical year with a combination of common years of 365 days and leap years of 366 days. A leap year is any year divisible by four, unless it is a century year, which must be divisible by 400 to be a leap year. Thus, 1700, 1800, and 1900 were not leap years, but 2000 will be. A critical mistake was made by John Hamilton Moore in calling 1800 a leap year, causing an error in the tables in his book, *The Practical Navigator*. This error caused the loss of at least one ship and was later discovered by Nathaniel Bowditch while writing the first edition of *The New American Practical Navigator*.

See Chapter 18 for an in-depth discussion of time.

1522. Eclipses

If the orbit of the moon coincided with the plane of the ecliptic, the moon would pass in front of the sun at every new moon, causing a solar eclipse. At full moon, the moon would pass through the earth's shadow, causing a lunar eclipse. Because of the moon's orbit is inclined 5° with respect to the ecliptic, the moon usually passes above or below the sun at new moon and above or below the earth's shadow at full moon. However, there are two points at which the plane of the moon's orbit intersects the ecliptic. These are the **nodes** of the moon's orbit. If the moon passes one of these points at the same time as the sun, a **solar eclipse** takes place. This is shown in Figure 1522.

The sun and moon are of nearly the same apparent size to an observer on the earth. If the moon is at perigee, the moon's apparent diameter is larger than that of the sun, and its shadow reaches the earth as a nearly round dot only a few miles in diameter. The dot moves rapidly across the earth, from west to east, as the moon continues in its orbit. Within the dot, the sun is completely hidden from view, and a total eclipse of the sun occurs. For a considerable distance around the shadow, part of the surface of the sun is obscured, and a **partial eclipse** occurs. In the line of travel of the shadow a partial eclipse occurs as the round disk of the moon appears to move slowly across the surface of the sun, hiding an ever-increasing part of it, until the total eclipse occurs. Because of the uneven edge of the mountainous moon, the light is not cut off evenly. But several last illuminated portions appear through the valleys or passes between the mountain peaks. These are called **Baily's Beads**. A total eclipse is a spectacular phenomenon. As the last light from the sun is cut off, the solar **corona**, or envelope of thin, illuminated gas around the sun becomes visible. Wisps of more dense gas may appear as **solar prominences**. The only light reaching the observer is that diffused by the atmosphere surrounding the shadow. As the moon appears to continue on across the face of the sun, the sun finally emerges from the other side, first as Baily's Beads, and then as an ever widening crescent until no part of its surface is obscured by the moon.

The duration of a total eclipse depends upon how nearly the moon crosses the center of the sun, the location of the shadow on the earth, the relative orbital speeds of the moon and earth, and (principally) the relative apparent diameters of the sun and moon. The maximum length that can occur is a little more than seven minutes.

If the moon is near apogee, its apparent diameter is less than that of the sun, and its shadow does not quite reach the earth. Over a small area of the earth directly in line with the moon and sun, the moon appears as a black disk almost covering the surface of the sun, but with a thin ring of the sun around its edge. This **annular eclipse** occurs a little more often than a total eclipse.

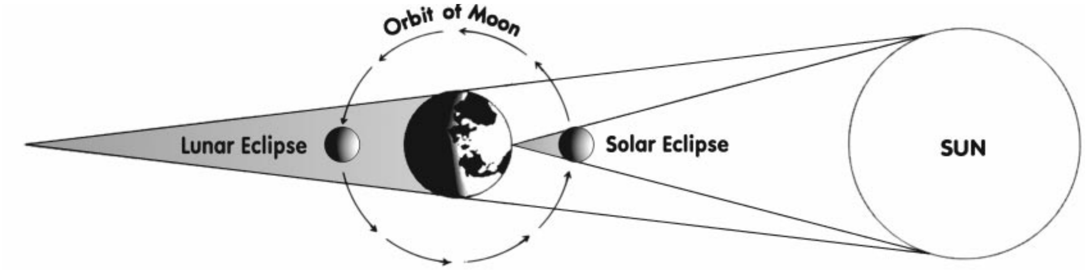


Figure 1522. Eclipses of the sun and moon.

If the shadow of the moon passes close to the earth, but not directly in line with it, a partial eclipse may occur without a total or annular eclipse.

An eclipse of the moon (or **lunar eclipse**) occurs when the moon passes through the shadow of the earth, as shown in Figure 1522. Since the diameter of the earth is about 3 $^1/_2$ times that of the moon, the earth's shadow at the distance of the moon is much larger than that of the moon. A total eclipse of the moon can last nearly 1 $^3/_4$ hours, and some part of the moon may be in the earth's shadow for almost 4 hours.

During a total solar eclipse no part of the sun is visible because the moon is in the line of sight. But during a lunar eclipse some light does reach the moon, diffracted by the atmosphere of the earth, and hence the eclipsed full moon is visible as a faint reddish disk. A lunar eclipse is visible over the entire hemisphere of the earth facing the moon. Anyone who can see the moon can see the eclipse.

During any one year there may be as many as five eclipses of the sun, and always there are at least two. There may be as many as three eclipses of the moon, or none. The total number of eclipses during a single year does not exceed seven, and can be as few as two. There are more solar than lunar eclipses, but the latter can be seen more often because of the restricted areas over which solar eclipses are visible.

The sun, earth, and moon are nearly aligned on the line of nodes twice each eclipse year of 346.6 days. This is less than a calendar year because of **regression of the nodes**. In a little more than 18 years the line of nodes returns to approximately the same position with respect to the sun, earth, and moon. During an almost equal period, called the **saros**, a cycle of eclipses occurs. During the following saros the cycle is repeated with only minor differences.

COORDINATES

1523. Latitude And Longitude

Latitude and **longitude** are coordinates used to locate positions on the earth. This section discusses three different definitions of these coordinates.

Astronomic latitude is the angle (ABQ, Figure 1523) between a line in the direction of gravity (AB) at a station and the plane of the equator (QQ'). **Astronomic longitude** is the angle between the plane of the celestial meridian at a station and the plane of the celestial meridian at Greenwich. These coordinates are customarily found by means of celestial observations. If the earth were perfectly homogeneous and round, these positions would be consistent and satisfactory. However, because of deflection of the vertical due to uneven distribution of the mass of the earth, lines of equal astronomic latitude and longitude are not circles, although the irregularities are small. In the United States the prime vertical component (affecting longitude) may be a little more than 18", and the meridional component (affecting latitude) as much as 25".

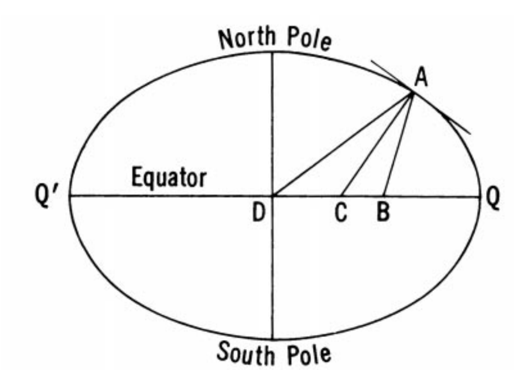


Figure 1523. Three kinds of latitude at point A.

Geodetic latitude is the angle (ACQ, Figure 1523) between a normal to the spheroid (AC) at a station and the plane of the geodetic equator (QQ'). **Geodetic longitude** is the angle between the plane defined by the normal to the spheroid and the axis of the earth and the plane of the geodetic meridian at Greenwich. These values are obtained when astronomical latitude and longitude are corrected for deflection of the vertical. These coordinates are used for charting and are frequently referred to as **geographic latitude** and **geographic longitude**, although these expressions are sometimes used to refer to astronomical latitude.

Geocentric latitude is the angle (ADQ, Figure 1523) at the center of the ellipsoid between the plane of its equator (QQ') and a straight line (AD) to a point on the surface of the earth. This differs from geodetic latitude because the earth is a spheroid rather than a sphere, and the meridians are ellipses. Since the parallels of latitude are considered to be circles, geodetic longitude is geocentric, and a separate expression is not used. The difference between geocentric and geodetic latitudes is a maximum of about 11.6' at latitude 45°.

Because of the oblate shape of the ellipsoid, the length of a degree of geodetic latitude is not everywhere the same, increasing from about 59.7 nautical miles at the equator to about 60.3 nautical miles at the poles. The value of 60 nautical miles customarily used by the navigator is correct at about latitude 45°.

MEASUREMENTS ON THE CELESTIAL SPHERE

1524. Elements Of The Celestial Sphere

The **celestial sphere** (section 1501) is an imaginary sphere of infinite radius with the earth at its center (Figure 1524a). The north and south celestial poles of this sphere are located by extension of the earth's axis. The **celestial equator** (sometimes called **equinoctial**) is formed by projecting the plane of the earth's equator to the celestial sphere. A **celestial meridian** is formed by the intersection of the plane of a terrestrial meridian and the celestial sphere. It is the arc of a great circle through the poles of the celestial sphere.

The point on the celestial sphere vertically overhead of an observer is the **zenith**, and the point on the opposite side of the sphere vertically below him is the **nadir**. The zenith and nadir are the extremities of a diameter of the celestial sphere through the observer and the common center of the earth and the celestial sphere. The arc of a celestial meridian between the poles is called the **upper branch** if it contains the zenith and the **lower branch** if it contains the nadir. The upper branch is frequently used in navigation, and references to a celestial meridian are understood to mean only its upper branch unless otherwise stated. Celestial meridians take the names of their terrestrial counterparts, such as 65° west.

An **hour circle** is a great circle through the celestial poles and a point or body on the celestial sphere. It is similar to a celestial meridian, but moves with the celestial sphere as it rotates about the earth, while a celestial meridian remains fixed with respect to the earth.

The location of a body on its hour circle is defined by the body's angular distance from the celestial equator. This distance, called **declination**, is measured north or south of the celestial equator in degrees, from 0° through 90°, similar to latitude on the earth.

A circle parallel to the celestial equator is called a **parallel of declination**, since it connects all points of equal declination. It is similar to a parallel of latitude on the earth. The path of a celestial body during its daily apparent revolution around the earth is called its **diurnal circle**. It is not

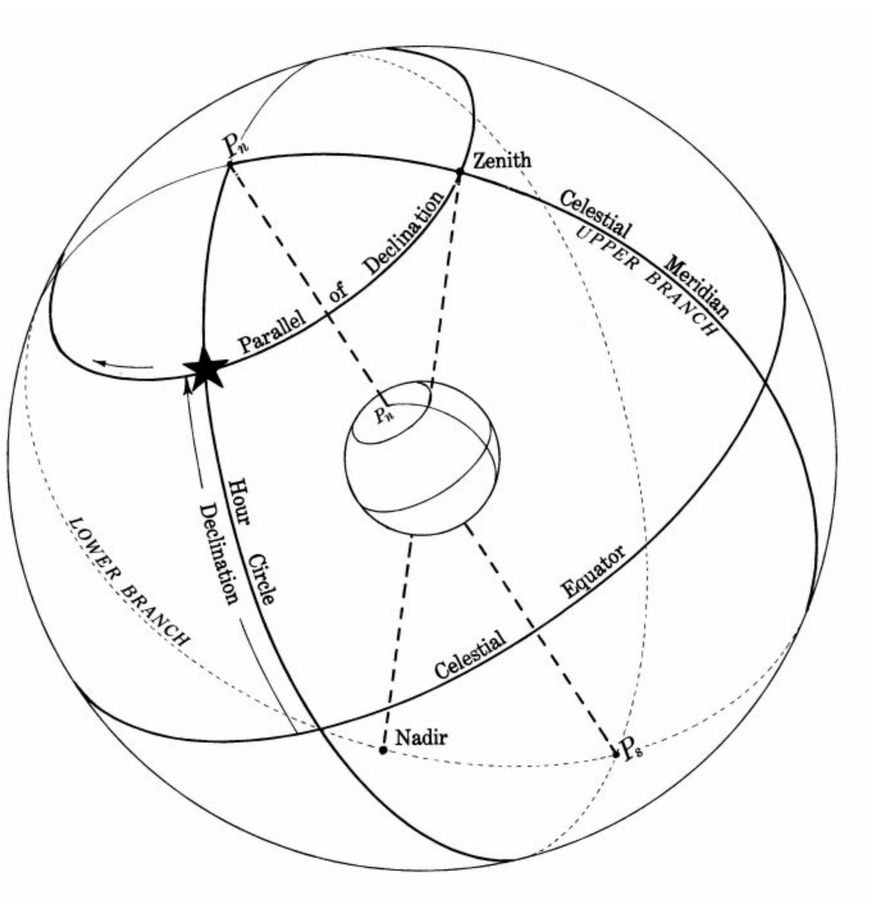


Figure 1524a. Elements of the celestial sphere. The celestial equator is the primary great circle.

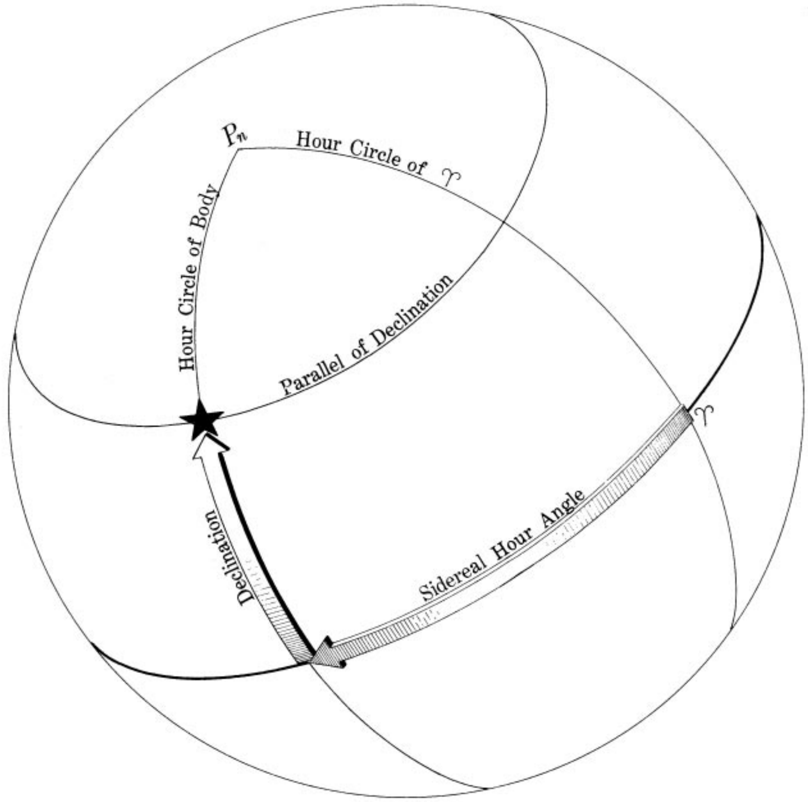


Figure 1524b. A point on the celestial sphere can be located by its declination and sidereal hour angle.

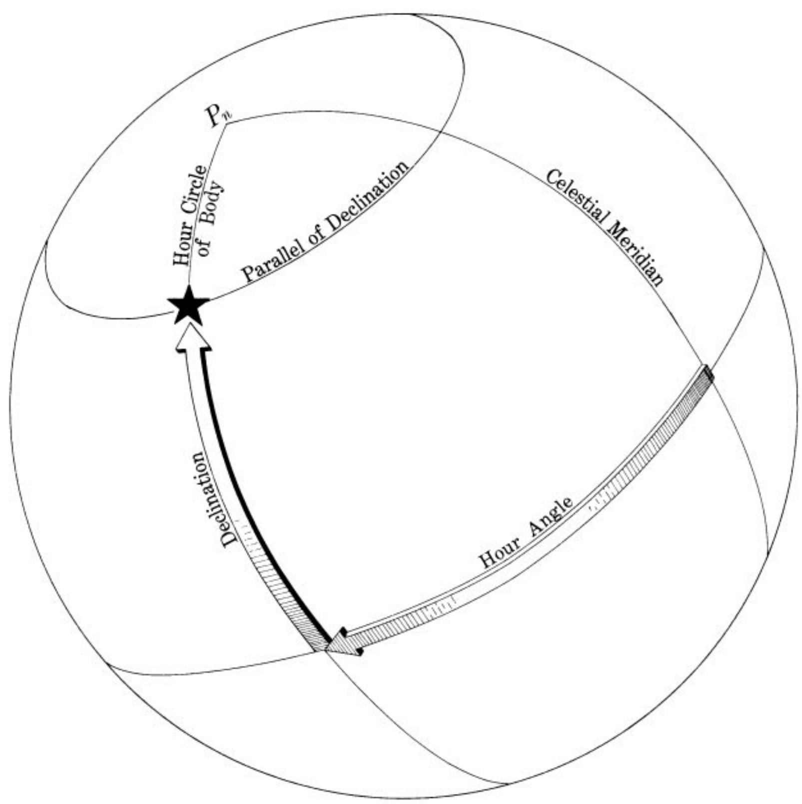


Figure 1524c. A point on the celestial sphere can be located by its declination and hour angle.

actually a circle if a body changes its declination. Since the declination of all navigational bodies is continually changing, the bodies are describing flat, spherical spirals as they circle the earth. However, since the change is relatively slow, a diurnal circle and a parallel of declination are usually considered identical.

A point on the celestial sphere may be identified at the intersection of its parallel of declination and its hour circle. The parallel of declination is identified by the declination.

Two basic methods of locating the hour circle are in use. First, the angular distance west of a reference hour circle through a point on the celestial sphere, called the vernal equinox or first point of Aries, is called **sidereal hour angle (SHA)** (Figure 1524b). This angle, measured eastward from the vernal equinox, is called **right ascension** and is usually expressed in time units.

The second method of locating the hour circle is to indicate its angular distance west of a celestial meridian (Figure 1524c). If the Greenwich celestial meridian is used as the reference, the angular distance is called **Greenwich hour angle (GHA)**, and if the meridian of the observer, it is called **local hour angle (LHA)**. It is sometimes more convenient to measure hour angle either eastward or westward, as longitude is measured on the earth, in which case it is called **meridian angle** (designated “t”).

A point on the celestial sphere may also be located using altitude and azimuth coordinates based upon the horizon as the primary great circle instead of the celestial equator.

COORDINATE SYSTEMS

1525. The Celestial Equator System Of Coordinates

If the familiar graticule of latitude and longitude lines is expanded until it reaches the celestial sphere of infinite radius, it forms the basis of the celestial equator system of coordinates. On the celestial sphere latitude becomes declination, while longitude becomes sidereal hour angle, measured from the vernal equinox.

Declination is angular distance north or south of the celestial equator (d in Figure 1525a). It is measured along an hour circle, from 0° at the celestial equator through 90° at the celestial poles. It is labeled N or S to indicate the direction of measurement. All points having the same declination lie along a parallel of declination.

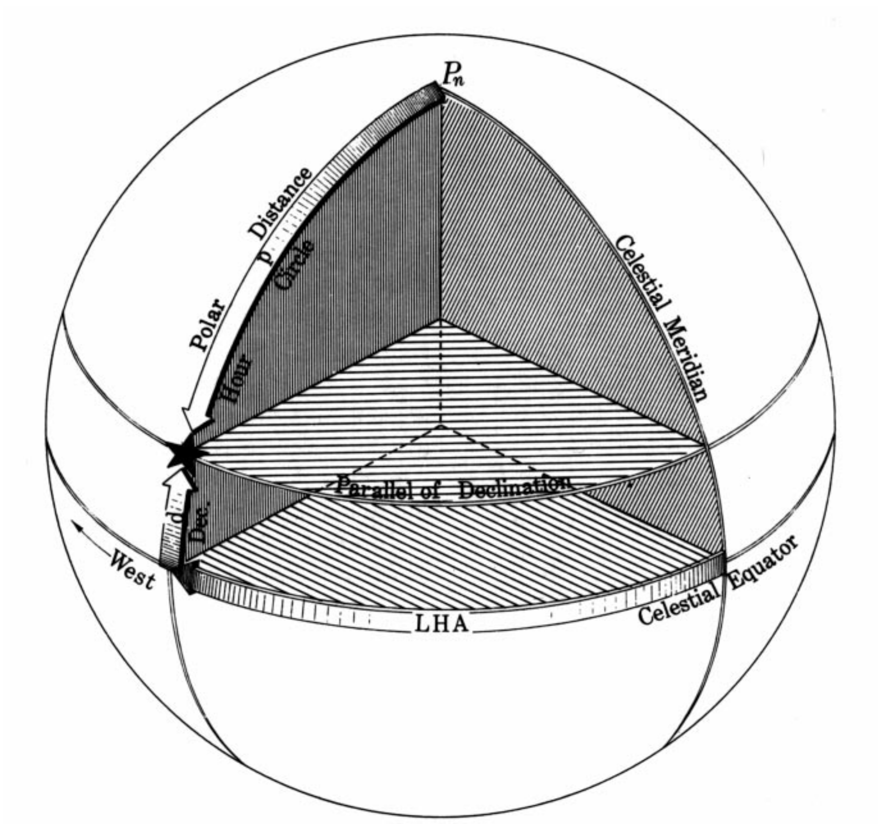


Figure 1525a. The celestial equator system of coordinates, showing measurements of declination, polar distance, and local hour angle.

Polar distance (p) is angular distance from a celestial pole, or the arc of an hour circle between the celestial pole and a point on the celestial sphere. It is measured along an hour circle and may vary from 0° to 180°, since either pole may be used as the origin of measurement. It is usually considered the complement of declination, though it may be either 90° – d or 90° + d, depending upon the pole used.

Local hour angle (LHA) is angular distance west of the local celestial meridian, or the arc of the celestial equator between the upper branch of the local celestial meridian and the hour circle through a point on the celestial sphere, measured westward from the local celestial meridian, through 360°. It is also the similar arc of the parallel of declination and the angle at the celestial pole, similarly measured. If the Greenwich (0°) meridian is used as the reference, instead of the local meridian, the expression **Greenwich hour angle (GHA)** is applied. It is sometimes convenient to measure the arc or angle in either an easterly or westerly direction from the local meridian, through 180°, when it is called **meridian angle (t)** and labeled E or W to indicate the direction of measurement. All bodies or other points having the same hour angle lie along the same hour circle.

Because of the apparent daily rotation of the celestial sphere, hour angle continually increases, but meridian angle increases from 0° at the celestial meridian to 180°W, which is also 180°E, and then decreases to 0° again. The rate of change for the mean sun is 15° per hour. The rate of all other bodies except the moon is within 3' of this value.

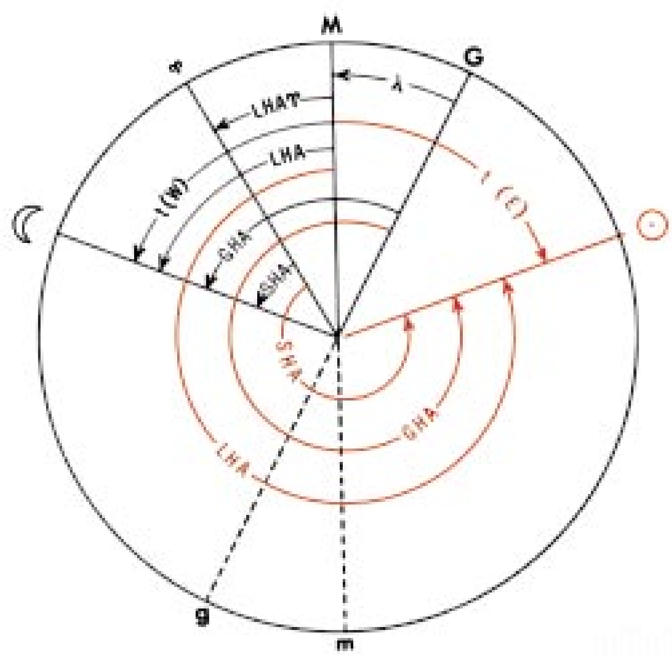


Figure 1525b. Time diagram. Local hour angle, Greenwich hour angle, and sidereal hour angle are measured westward through 360°. Meridian angle is measured eastward or westward through 180° and labeled E or W to indicate the direction of measurement.

The average rate of the moon is about 15.5°.

As the celestial sphere rotates, each body crosses each branch of the celestial meridian approximately once a day. This crossing is called **meridian transit** (sometimes called culmination). It may be called **upper transit** to indicate crossing of the upper branch of the celestial meridian, and **lower transit** to indicate crossing of the lower branch.

The **time diagram** shown in Figure 1525b illustrates the relationship between the various hour angles and meridian angle. The circle is the celestial equator as seen from above the South Pole, with the upper branch of the observer's meridian (P_sM) at the top. The radius P_sG is the Greenwich meridian; P_s ♈ is the hour circle of the vernal equinox. The sun's hour circle is to the east of the observer's meridian; the moon's hour circle is to the west of the observer's meridian Note that when LHA is less than 180°, t is numerically the same and is labeled W, but that when LHA is greater than 180°, t = 360° – LHA and is labeled E. In Figure 1525b arc GM is the longitude, which in this case is west. The relationships shown apply equally to other arrangements of radii, except for relative magnitudes of the quantities involved.

1526. The Horizons

The second set of celestial coordinates with which the navigator is directly concerned is based upon the horizon as the primary great circle. However, since several different horizons are defined, these should be thoroughly understood before proceeding with a consideration of the horizon system of coordinates.

The line where earth and sky appear to meet is called the **visible** or **apparent horizon**. On land this is usually an irregular line unless the terrain is level. At sea the visible horizon appears very regular and often very sharp. However, its position relative to the celestial sphere depends primarily upon (1) the refractive index of the air and (2) the height of the observer's eye above the surface.

Figure 1526 shows a cross section of the earth and celestial sphere through the position of an observer at A above the surface of the earth. A straight line through A and the center of the earth O is the vertical of the observer and contains his zenith (Z) and nadir (Na). A plane perpendicular to the true vertical is a horizontal plane, and its intersection with the celestial sphere is a horizon. It is the **celestial horizon** if the plane passes through the center of the earth, the **geoidal horizon** if it is tangent to the earth, and the **sensible horizon** if it passes through the eye of the observer at A. Since the radius of the earth is considered negligible with respect to that of the celestial sphere, these horizons become superimposed, and most measurements are referred only to the celestial horizon. This is sometimes called the **rational horizon**.

If the eye of the observer is at the surface of the earth, his visible horizon coincides with the plane of the geoidal horizon; but when elevated above the surface, as at A, his eye becomes the vertex of a cone which is tangent to the earth atthe small circle BB, and which intersects the celestial

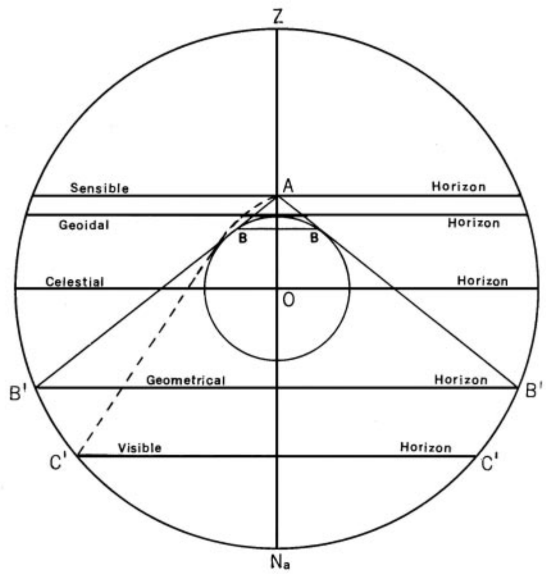


Figure 1526. The horizons used in navigation.

sphere in B'B', the **geometrical horizon**. This expression is sometimes applied to the celestial horizon.

Because of refraction, the visible horizon C'C' appears above but is actually slightly below the geometrical horizon as shown in Figure 1526.

For any elevation above the surface, the celestial horizon is usually above the geometrical and visible horizons, the difference increasing as elevation increases. It is thus possible to observe a body which is above the visible horizon but below the celestial horizon. That is, the body's altitude is negative and its zenith distance is greater than 90°.

1527. The Horizon System Of Coordinates

This system is based upon the celestial horizon as the primary great circle and a series of secondary vertical circles which are great circles through the zenith and nadir of the observer and hence perpendicular to his horizon (Figure 1527a). Thus, the celestial horizon is similar to the equator, and the vertical circles are similar to meridians, but with one important difference. The celestial horizon and vertical circles are dependent upon the position of the observer and hence move with him as he changes position, while the primary and secondary great circles of both the geographical and celestial equator systems are independent of the observer. The horizon and celestial equator systems coincide for an observer at the geographical pole of the earth and are mutually perpendicular for an observer on the equator. At all other places the two are oblique.

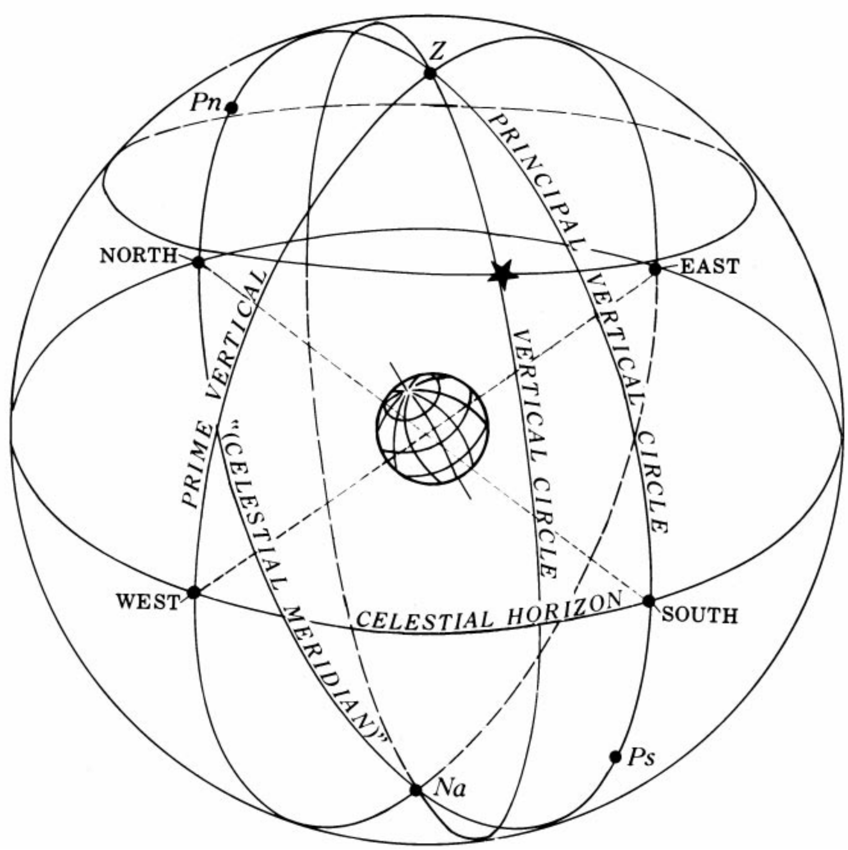


Figure 1527a. Elements of the celestial sphere. The celestial horizon is the primary great circle.

The vertical circle through the north and south points of the horizon passes through the poles of the celestial equator system of coordinates. One of these poles (having the same name as the latitude) is above the horizon and is called the **elevated pole**. The other, called the **depressed pole**, is below the horizon. Since this vertical circle is a great circle through the celestial poles, and includes the zenith of the observer, it is also a celestial meridian. In the horizon system it is called the **principal vertical circle**. The vertical circle through the east and west points of the horizon, and hence perpendicular to the principal vertical circle, is called the **prime vertical circle**, or simply the **prime vertical**.

As shown in Figure 1527b, altitude is angular distance above the horizon. It is measured along a vertical circle, from 0° at the horizon through 90° at the zenith. Altitude measured from the visible horizon may exceed 90° because of the dip of the horizon, as shown in Figure 1526. Angular distance below the horizon, called negative altitude, is provided for by including certain negative altitudes in some tables for use in celestial navigation. All points having the same altitude lie along a parallel of altitude.

Zenith distance (z) is angular distance from the zenith, or the arc of a vertical circle between the zenith and a point on the celestial sphere. It is measured along a vertical circle from 0° through 180°. It is usually considered the complement of altitude. For a body above the celestial horizon it is equal to 90° – h and for a body below the celestial horizon it is equal to 90° – (– h) or 90° + h.

The horizontal direction of a point on the celestial sphere, or the bearing of the geographical position, is called **azimuth** or **azimuth angle** depending upon the method of measurement. In both methods it is an arc of the horizon (or parallel of altitude), or an angle at the zenith. It is **azimuth** (Zn) if measured clockwise through 360°, starting at the north point on the horizon, and **azimuth angle** (Z) if measured either clockwise or counterclockwise through 180°, starting at the north point of the horizon in north latitude and the south point of the horizon in south latitude.

The ecliptic system is based upon the ecliptic as the primary great circle, analogous to the equator. The points 90° from the ecliptic are the north and south ecliptic poles. The series of great circles through these poles, analogous to meridians, are circles of latitude. The circles parallel to the plane of the ecliptic, analogous to parallels on the earth, are parallels of latitude or circles of longitude. Angular distance north or south of the ecliptic, analogous to latitude, is celestial latitude. Celestial longitude is measured eastward along the ecliptic through 360°, starting at the vernal equinox. This system of coordinates is of interest chiefly to astronomers.

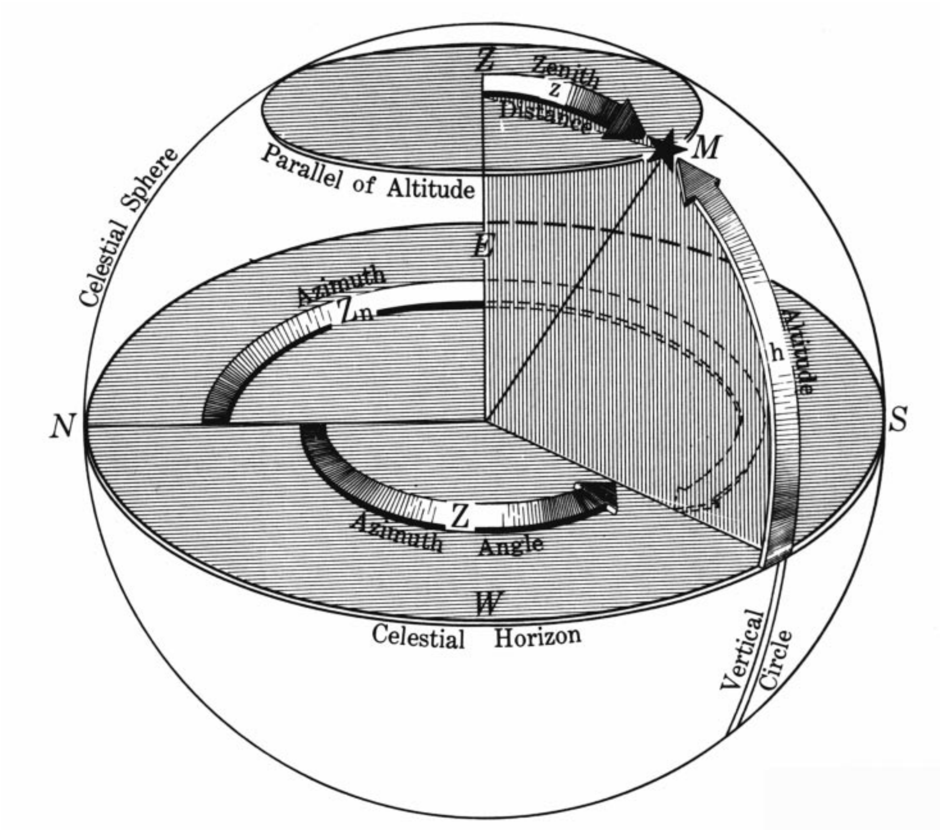


Figure 1527b. The horizon system of coordinates, showing measurement of altitude, zenith distance, azimuth, and azimuth angle.

Earth	*Celestial Equator*	*Horizon*	*Ecliptic*
equator	celestial equator	horizon	ecliptic
poles	celestial poles	zenith; nadir	ecliptic poles
meridians	hours circle; celestial meridians	vertical circles	circles of latitude
prime meridian	hour circle of Aries	principal or prime vertical circle	circle of latitude through Aries
parallels	parallels of declination	parallels of altitude	parallels of latitude
latitude	declination	altitude	celestial altitude
colatitude	polar distance	zenith distance	celestial colatitude
longitude	SHA; RA; GHA; LHA; t	azimuth; azimuth angle; amplitude	celestial longitude

Figure 1528. The four systems of celestial coordinates and their analogous terms.

1528. Summary Of Coordinate Systems

The four systems of celestial coordinates are analogous to each other and to the terrestrial system, although each has distinctions such as differences in directions, units, and limits of measurement. Figure 1528 indicates the analogous term or terms under each system.

1529. Diagram On The Plane Of The Celestial Meridian

From an imaginary point outside the celestial sphere and over the celestial equator, at such a distance that the view would be orthographic, the great circle appearing as the outer limit would be a celestial meridian. Other celestial meridians would appear as ellipses. The celestial equator

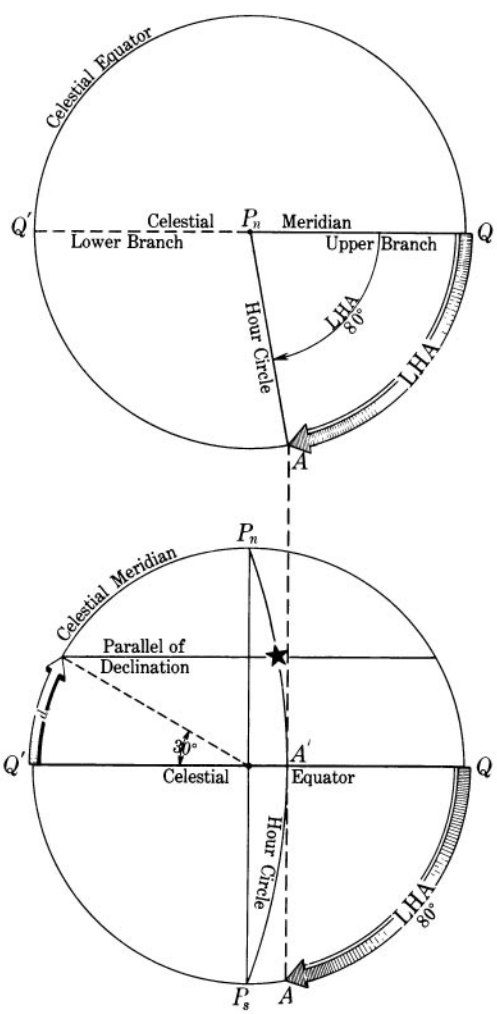


Figure 1529a. Measurement of celestial equator system of coordinates.

Figure 1529b. Measurement of horizon system of coordinates.

would appear as a diameter 90° from the poles, and parallels of declination as straight lines parallel to the equator. The view would be similar to an orthographic map of the earth.

A number of useful relationships can be demonstrated by drawing a diagram on the plane of the celestial meridian showing this orthographic view. Arcs of circles can be substituted for the ellipses without destroying the basic relationships. Refer to Figure 1529a. In the lower diagram the circle represents the celestial meridian, QQ' the celestial equator, Pn and Ps the north and south celestial poles, respectively. If a star has a declination of 30° N, an angle of 30° can be measured from the celestial equator, as shown. It could be measured either to the right or left, and would have been toward the south pole if the declination had been south. The parallel of declination is a line through this point and parallel to the celestial equator. The star is somewhere on this line (actually a circle viewed on edge).

To locate the hour circle, draw the upper diagram so that Pn is directly above Pn of the lower figure (in line with the polar axis Pn-Ps), and the circle is of the same diameter as that of the lower figure. This is the plan view, looking down on the celestial sphere from the top. The circle is the celestial equator. Since the view is from above the north celestial pole, west is clockwise. The diameter QQ' is the celestial meridian shown as a circle in the lower diagram. If the right half is considered the upper branch, local hour angle is measured clockwise from this line to the hour circle, as shown. In this case the LHA is 80°. The intersection of the hour circle and celestial equator, point A, can be projected down to the lower diagram (point A') by a straight line parallel to the polar axis. The elliptical hour circle can be represented approximately by an arc of a circle through A', Pn, Ps. The center of this circle is somewhere along the celestial equator line QQ', extended if necessary. It is usually found by trial and error. The intersection of the hour circle and parallel of declination locates the star.

Since the upper diagram serves only to locate point A' in the lower diagram, the two can be combined. That is, the LHA arc can be drawn in the lower diagram, as shown, and point A projected upward to A'. In practice, the upper diagram is not drawn, being shown here for illustrative purposes.

In this example the star is on that half of the sphere toward the observer, or the western part. If LHA had been greater than 180°, the body would have been on the eastern or "back" side.

From the east or west point over the celestial horizon, the orthographic view of the horizon system of coordinates would be similar to that of the celestial equator system from a point over the celestial equator, since the celestial meridian is also the principal vertical circle. The horizon would appear as a diameter, parallels of altitude as straight lines parallel to the horizon, the zenith and nadir as poles 90° from the horizon, and vertical circles as ellipses through the zenith and nadir, except for the principal vertical circle, which would appear as a circle, and the prime vertical, which would appear as a diameter perpendicular to the horizon.

A celestial body can be located by altitude and azimuth in a manner similar to that used with the celestial equator system. If the altitude is 25°, this angle is measured from the horizon toward the zenith and the parallel of altitude is drawn as a straight line parallel to the horizon, as shown at hh' in the lower diagram of Figure 1529b. The plan view from above the zenith is shown in the upper diagram. If north is taken at the left, as shown, azimuths are measured clockwise from this point. In the figure the azimuth is 290° and the azimuth angle is N70°W. The vertical circle is located by measuring either arc. Point A thus located can be projected vertically downward to A' on the horizon of the lower diagram, and the vertical circle represented approximately by the arc of a circle through A' and the zenith and nadir. The center of this circle is on NS, extended if necessary. The body is at the intersection of the parallel of altitude and the vertical circle. Since the upper diagram serves only to locate A' on the lower diagram, the two can be combined, point A located on the lower diagram and projected upward to A', as shown. Since the body of the example has an azimuth greater than 180°, it is on the western or "front" side of the diagram.

Since the celestial meridian appears the same in both the celestial equator and horizon systems, the two diagrams can be combined and, if properly oriented, a body can be located by one set of coordinates, and the coordinates of the other system can be determined by measurement.

Refer to Figure 1529c, in which the black lines represent the celestial equator system, and the red lines the horizon system. By convention, the zenith is shown at the top and the north point of the horizon at the left. The west point on the horizon is at the center, and the east point directly behind it. In the figure the latitude is 37°N. Therefore, the zenith is 37° north of the celestial equator. Since the zenith is established at the top of the diagram, the equator can be found by measuring an arc of 37° toward the south, along the celestial meridian. If the declination is 30°N and the LHA is 80°, the body can be located as shown by the black lines, and described above.

The altitude and azimuth can be determined by the reverse process to that described above. Draw a line hh' through the body and parallel to the horizon, NS. The altitude, 25°, is found by measurement, as shown. Draw the arc of a circle through the body and the zenith and nadir. From A', the intersection of this arc with the horizon, draw a vertical line intersecting the circle at A. The azimuth, N70°W, is found by measurement, as shown. The prefix N is applied to agree with the latitude. The body is left (north) of ZNa, the prime vertical circle. The suffix W applies because the LHA, 80°, shows that the body is west of the meridian.

If altitude and azimuth are given, the body is located by means of the red lines. The parallel of declination is then drawn parallel to QQ', the celestial equator, and the declination determined by measurement. Point L' is located by drawing the arc of a circle through Pn, the star, and Ps. From L' a line is drawn perpendicular to QQ', locating L. The meridian angle is then found by measurement. The dec-

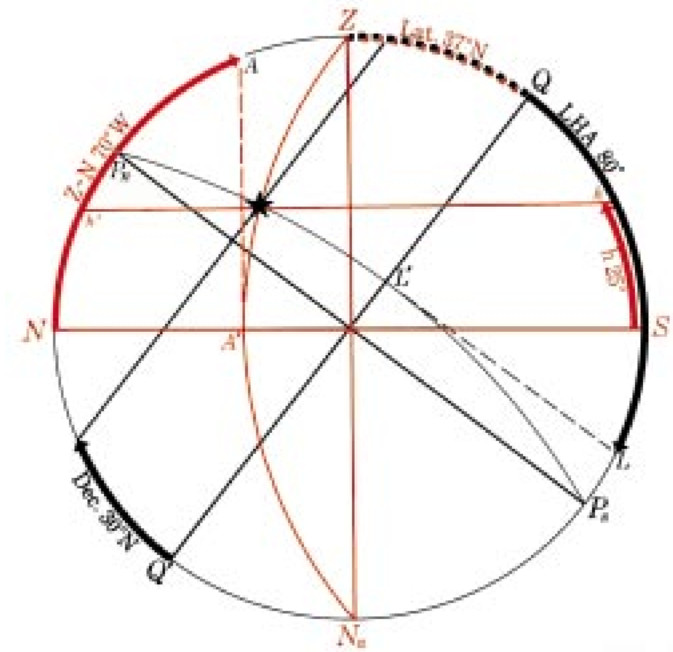


Figure 1529c. Diagram on the plane of the celestial meridian.

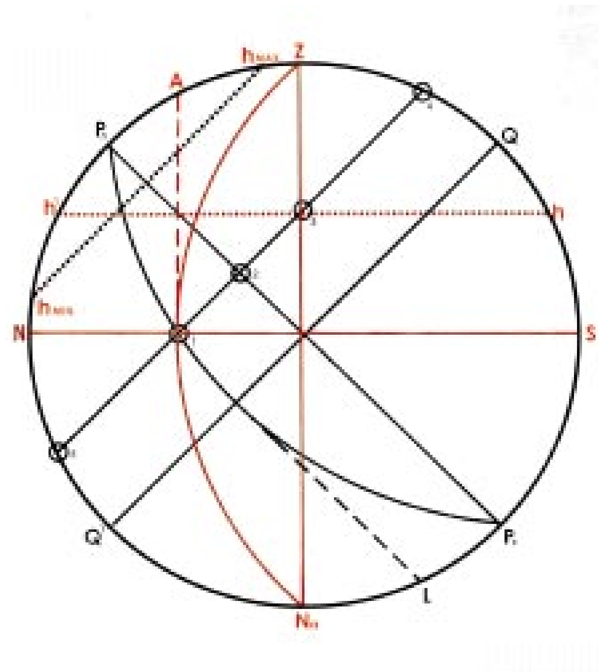


Figure 1529d. A diagram on the plane of the celestial meridian for lat. 45°N.

lination is known to be north because the body is between the celestial equator and the north celestial pole. The meridian angle is west, to agree with the azimuth, and hence LHA is numerically the same.

Since QQ'and PnPs are perpendicular, and ZNa and NS are also perpendicular, arc NPn is equal to arc ZQ. That is, the altitude of the elevated pole is equal to the declination of the zenith, which is equal to the latitude. This relationship is the basis of the method of determining latitude by an observation of Polaris.

The diagram on the plane of the celestial meridian is useful in approximating a number of relationships. Consider Figure 1529d. The latitude of the observer (NPn or ZQ) is 45°N. The declination of the sun (Q4) is 20°N. Neglecting the change in declination for one day, note the following: At sunrise, position 1, the sun is on the horizon (NS), at the "back" of the diagram. Its altitude, h, is 0°. Its azimuth angle, Z, is the arc NA, N63°E. This is prefixed N to agree with the latitude and suffixed E to agree with the meridian angle of the sun at sunrise. Hence, Zn = 063°. The amplitude, A, is the arc ZA, E27°N. The meridian angle, t, is the arc QL, 110°E. The suffix E is applied because the sun is east of the meridian at rising. The LHA is 360° – 110° = 250°.

As the sun moves upward along its parallel of declination, its altitude increases. It reaches position 2 at about 0600, when t = 90°E. At position 3 it is on the prime vertical, ZNa. Its azimuth angle, Z, is N90°E, and Zn = 090°. The altitude is Nh' or Sh, 27°.

Moving on up its parallel of declination, it arrives at position 4 on the celestial meridian about noon-when t and LHA are both 0°, by definition. On the celestial meridian a body's azimuth is 000° or 180°. In this case it is 180° because the body is south of the zenith. The maximum altitude occurs at meridian transit. In this case the arc S4 represents the maximum altitude, 65°. The zenith distance, z, is the arc Z4, 25°. A body is not in the zenith at meridian transit unless its declination's magnitude and name are the same as the latitude.

Continuing on, the sun moves downward along the "front" or western side of the diagram. At position 3 it is again on the prime vertical. The altitude is the same as when previously on the prime vertical, and the azimuth angle is numerically the same, but now measured toward the west. The azimuth is 270°. The sun reaches position 2 six hours after meridian transit and sets at position 1. At this point, the azimuth angle is numerically the same as at sunrise, but westerly, and Zn = 360° – 63° = 297°. The amplitude is W27°N.

After sunset the sun continues on downward, along its parallel of declination, until it reaches position 5, on the lower branch of the celestial meridian, about midnight. Its negative altitude, arc N5, is now greatest, 25°, and its azimuth is 000°. At this point it starts back up along the "back" of the diagram, arriving at position 1 at the next sunrise, to start another cycle.

Half the cycle is from the crossing of the 90° hour circle (the PnPs line, position 2) to the upper branch of the celestial meridian (position 4) and back to the PnPs line (position 2). When the declination and latitude have the same name (both north or both south), more than half the parallel of declination (position 1 to 4 to 1) is above the horizon, and the body is above the horizon more than half the time, crossing the 90° hour circle above the horizon. It rises and sets on the same side of the prime vertical as the elevated pole. If the declina-

tion is of the same name but numerically smaller than the latitude, the body crosses the prime vertical above the horizon. If the declination and latitude have the same name and are numerically equal, the body is in the zenith at upper transit. If the declination is of the same name but numerically greater than the latitude, the body crosses the upper branch of the celestial meridian between the zenith and elevated pole and does not cross the prime vertical. If the declination is of the same name as the latitude and complementary to it (d + L = 90°), the body is on the horizon at lower transit and does not set. If the declination is of the same name as the latitude and numerically greater than the colatitude, the body is above the horizon during its entire daily cycle and has maximum and minimum altitudes. This is shown by the black dotted line in Figure 1529d.

If the declination is 0° at any latitude, the body is above the horizon half the time, following the celestial equator QQ', and rises and sets on the prime vertical. If the declination is of contrary name (one north and the other south), the body is above the horizon less than half the time and crosses the 90° hour circle below the horizon. It rises and sets on the opposite side of the prime vertical from the elevated pole. If the declination is of contrary name and numerically smaller than the latitude, the body crosses the prime vertical below the horizon. This is the situation with the sun in winter follows when days are short. If the declination is of contrary name and numerically equal to the latitude, the body is in the nadir at lower transit. If the declination is of contrary name and complementary to the latitude, the body is on the horizon at upper transit. If the declination is of contrary name and numerically greater than the colatitude, the body does not rise.

All of these relationships, and those that follow, can be derived by means of a diagram on the plane of the celestial meridian. They are modified slightly by atmospheric refraction, height of eye, semidiameter, parallax, changes in declination, and apparent speed of the body along its diurnal circle.

It is customary to keep the same orientation in south latitude, as shown in Figure 1529e. In this illustration the latitude is 45°S, and the declination of the body is 15°N. Since Ps is the elevated pole, it is shown above the southern horizon, with both SPs and ZQ equal to the latitude, 45°. The body rises at position 1, on the opposite side of the prime vertical from the elevated pole. It moves upward along its parallel of declination to position 2, on the upper branch of the celestial meridian, bearing north; and then it moves downward along the “front” of the diagram to position 1, where it sets. It remains above the horizon for less than half the time because declination and latitude are of contrary name. The azimuth at rising is arc NA, the amplitude ZA, and the azimuth angle SA. The altitude circle at meridian transit is shown at hh'.

A diagram on the plane of the celestial meridian can be used to demonstrate the effect of a change in latitude. As the latitude increases, the celestial equator becomes more nearly parallel to the horizon. The colatitude becomes smaller,

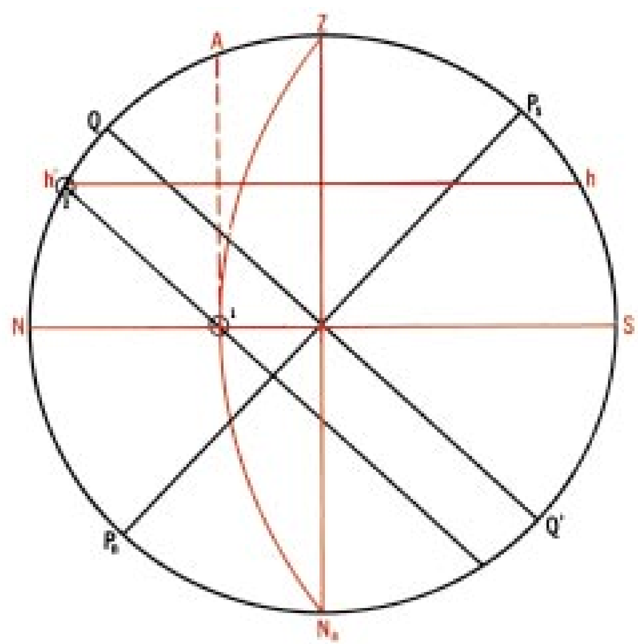


Figure 1529e. A diagram on the plane of the celestial meridian for lat. 45°S.

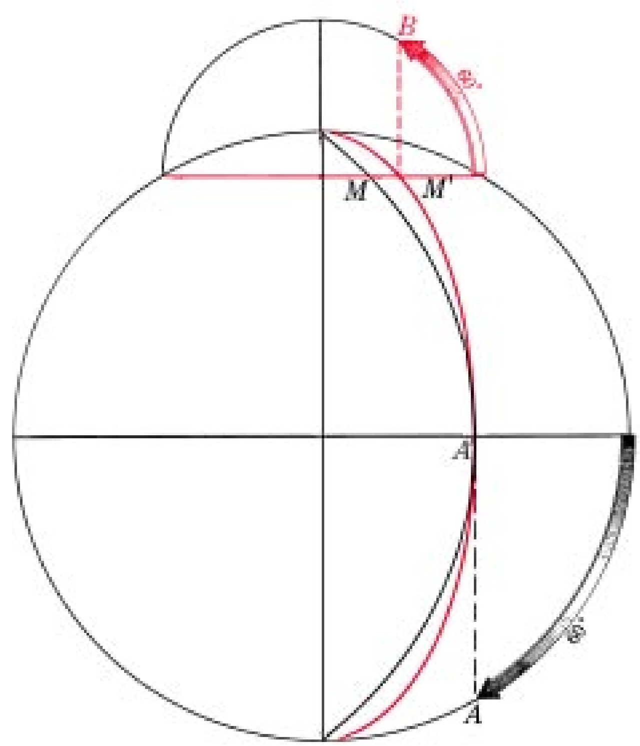


Figure 1529f. Locating a point on an ellipse of a diagram on the plane of the celestial meridian.

NAVIGATIONAL COORDINATES

Coordinate	Symbol	Measured from	Measured along	Direction	Measured to	Units	Precision	Maximum value	Labels
latitude	L, lat.	equator	meridian	N, S	parallel	°, ′	0′.1	90°	N, S
colatitude	colat.	poles	meridian	S, N	parallel	°, ′	0′.1	90°	—
longitude	λ, long.	prime meridian	parallel	E, W	local meridian	°, ′	0′.1	180°	E, W
declination	d, dec.	celestial equator	hour circle	N, S	parallel of declination	°, ′	0′.1	90°	N, S
polar distance	p	elevated pole	hour circle	S, N	parallel of declination	°, ′	0′.1	180°	—
altitude	h	horizon	vertical circle	up	parallel of altitude	°, ′	0′.1	90°*	—
zenith distance	z	zenith	vertical circle	down	parallel of altitude	°, ′	0′.1	180°	—
azimuth	Zn	north	horizon	E	vertical circle	°	0°.1	360°	—
azimuth angle	Z	north, south	horizon	E, W	vertical circle	°	0°.1	180° or 90°	N, S...E, W
amplitude	A	east, west	horizon	N, S	body	°	0°.1	90°	E, W...N, S
Greenwich hour angle	GHA	Greenwich celestial meridian	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
local hour angle	LHA	local celestial meridian	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
meridian angle	t	local celestial meridian	parallel of declination	E, W	hour circle	°, ′	0′.1	180°	E, W
sidereal hour angle	SHA	hour circle of vernal equinox	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
right ascension	RA	hour circle of vernal equinox	parallel of declination	E	hour circle	h, m, s	1^s	24^h	—
Greenwich mean time	GMT	lower branch Greenwich celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
local mean time	LMT	lower branch local celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
zone time	ZT	lower branch zone celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
Greenwich apparent time	GAT	lower branch Greenwich celestial meridian	parallel of declination	W	hour circle apparent sun	h, m, s	1^s	24^h	—
local apparent time	LAT	lower branch local celestial meridian	parallel of declination	W	hour circle apparent sun	h, m, s	1^s	24^h	—
Greenwich sidereal time	GST	Greenwich celestial meridian	parallel of declination	W	hour circle vernal equinox	h, m, s	1^s	24^h	—
local sidereal time	LST	local celestial meridian	parallel of declination	W	hour circle vernal equinox	h, m, s	1^s	24^h	—

*When measured from celestial horizon.

Figure 1529g. Navigational Coordinates.

increasing the number of circumpolar bodies and those which neither rise nor set. It also increases the difference in the length of the days between summer and winter. At the poles celestial bodies circle the sky, parallel to the horizon. At the equator the 90° hour circle coincides with the horizon. Bodies rise and set vertically; and are above the horizon half the time. At rising and setting the amplitude is equal to the declination. At meridian transit the altitude is equal to the codeclination. As the latitude changes name, the same-contrary name relationship with declination reverses. This accounts for the fact that one hemisphere has winter while the other is having summer.

The error arising from showing the hour circles and vertical circles as arcs of circles instead of ellipses increases with increased declination or altitude. More accurate results can be obtained by measurement of azimuth on the parallel of altitude instead of the horizon, and of hour angle on the parallel of declination instead of the celestial equator. Refer to Figure 1529f. The vertical circle shown is for a body having an azimuth angle of S60°W. The arc of a circle is shown in black, and the ellipse in red. The black arc is obtained by measurement around the horizon, locating A' by means of A, as previously described. The intersection of this arc with the altitude circle at 60° places the body at M. If a semicircle is drawn with the altitude circle as a diameter, and the azimuth angle measured around this, to B, a perpendicular to the hour circle locates the body at M', on the ellipse. By this method the altitude circle, rather than the horizon, is, in effect, rotated through 90° for the measurement. This refinement is seldom used because actual values are usually found mathematically, the diagram on the plane of the meridian being used primarily to indicate relationships.

With experience, one can visualize the diagram on the plane of the celestial meridian without making an actual drawing. Devices with two sets of spherical coordinates, on either the orthographic or stereographic projection, pivoted at the center, have been produced commercially to provide a mechanical diagram on the plane of the celestial meridian. However, since the diagram's principal use is to illustrate certain relationships, such a device is not a necessary part of the navigator's equipment.

Figure 1529g summarizes navigation coordinate systems.

1530. The Navigational Triangle

A triangle formed by arcs of great circles of a sphere is called a **spherical triangle**. A spherical triangle on the celestial sphere is called a **celestial triangle**. The spherical triangle of particular significance to navigators is called the **navigational triangle**, formed by arcs of a *celestial meridian*, an *hour circle*, and a *vertical circle*. Its vertices are the *elevated pole*, the *zenith*, and a *point on the celestial sphere* (usually a celestial body). The terrestrial counterpart is also called a navigational triangle, being formed by arcs of two meridians and the great circle connecting two places on the earth, one on each meridian. The vertices are the two places and a pole. In great-circle sailing these places are the point of departure and the destination. In celestial navigation they are the assumed position (AP) of the observer and the geographical position (GP) of the body (the place having the body in its zenith). The GP of the sun is sometimes called the **subsolar point**, that of the moon the **sublunar point**, that of a satellite (either natural or artificial) the **subsatellite point**, and that of a star its **substellar** or **subastral point**. When used to solve a celestial observation, either the celestial or terrestrial triangle may be called the **astronomical triangle**.

The navigational triangle is shown in Figure 1530a on a diagram on the plane of the celestial meridian. The earth is at the center, O. The star is at M, dd' is its parallel of declination, and hh' is its altitude circle.

In the figure, arc QZ of the celestial meridian is the latitude of the observer, and PnZ, one side of the triangle, is the colatitude. Arc AM of the vertical circle is the altitude of the body, and side ZM of the triangle is the zenith distance, or coaltitude. Arc LM of the hour circle is the declination of the body, and side PnM of the triangle is the polar distance, or codeclination.

The angle at the elevated pole, ZPnM, having the hour circle and the celestial meridian as sides, is the meridian angle, t. The angle at the zenith, PnZM, having the vertical circle and that arc of the celestial meridian, which includes the elevated pole, as sides, is the azimuth angle. The angle at the celestial body, ZMPn, having the hour circle and the vertical circle as sides, is the parallactic angle (X) (sometimes called the position angle), which is not generally used

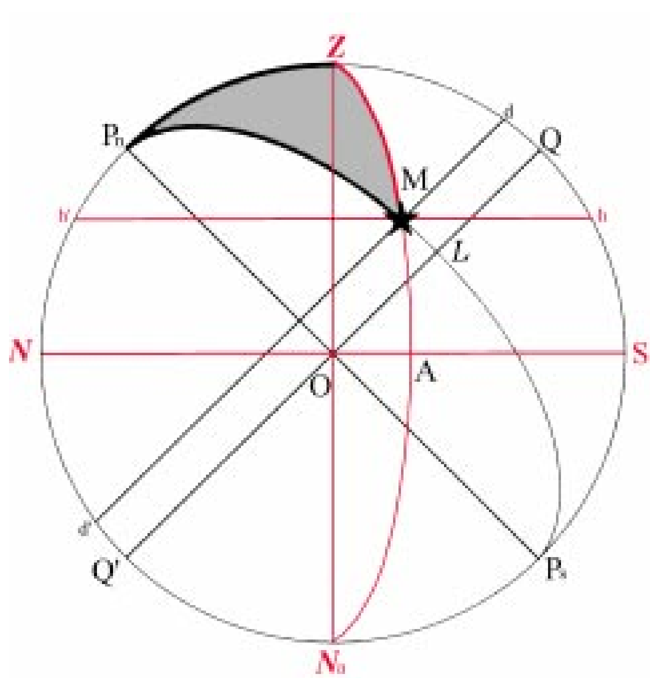


Figure 1530a. The navigational triangle.

by the navigator.

A number of problems involving the navigational triangle are encountered by the navigator, either directly or indirectly. Of these, the most common are:

1. Given latitude, declination, and meridian angle, to find altitude and azimuth angle. This is used in the reduction of a celestial observation to establish a line of position.
2. Given latitude, altitude, and azimuth angle, to find declination and meridian angle. This is used to identify an unknown celestial body.
3. Given meridian angle, declination, and altitude, to find azimuth angle. This may be used to find azimuth when the altitude is known.
4. Given the latitude of two places on the earth and the difference of longitude between them, to find the initial great-circle course and the great-circle distance. This involves the same parts of the triangle as in 1, above, but in the terrestrial triangle, and hence is defined differently.

Both celestial and terrestrial navigational triangles are shown in perspective in Figure 1530b.

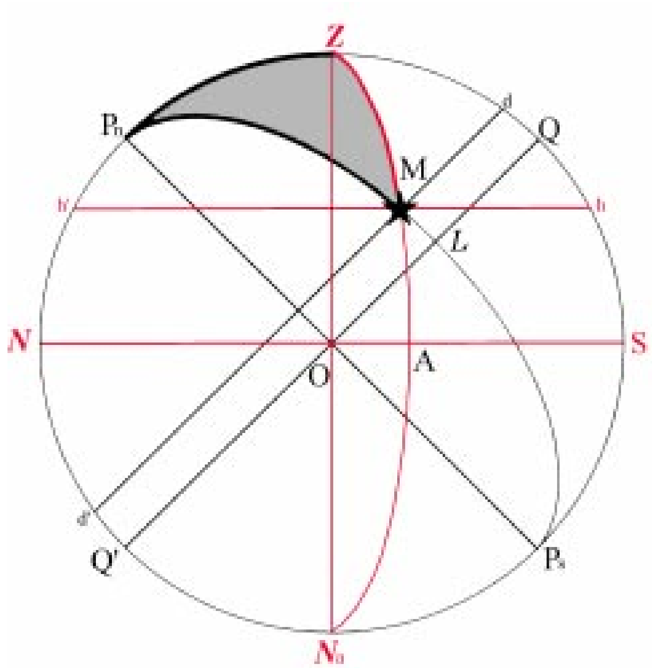


Figure 1530b. The navigational triangle in perspective.

IDENTIFICATION OF STARS AND PLANETS

1531. Introduction

A basic requirement of celestial navigation is the ability to identify the bodies observed. This is not difficult because relatively few stars and planets are commonly used for navigation, and various aids are available to assist in their identification. Some navigators may have access to a computer which can identify the celestial body observed given inputs of DR position and observed altitude. No problem is encountered in the identification of the sun and moon. However, the planets can be mistaken for stars. A person working continually with the night sky recognizes a planet by its changing position among the relatively fixed stars. The planets are identified by noting their positions relative to each other, the sun, the moon, and the stars. They remain within the narrow limits of the zodiac, but are in almost constant motion relative to the stars. The magnitude and color may be helpful. The information needed is found in the Nautical Almanac. The “Planet Notes” near the front of that volume are particularly useful.

Sometimes the light from a planet seems steadier than that from a star. This is because fluctuation of the unsteady atmosphere causes scintillation or twinkling of a star, which has no measurable diameter with even the most powerful telescopes. The navigational planets are less susceptible to the twinkling because of the broader apparent area giving light.

Planets can also be identified by planet diagram, star finder, sky diagram, or by computation.

1532. Stars

The Nautical Almanac lists full navigational information on 19 first magnitude stars and 38 second magnitude stars, plus Polaris. Abbreviated information is listed for 115 more. Additional stars are listed in The Astronomical Almanac and in various star catalogs. About 6,000 stars of the sixth magnitude or brighter (on the entire celestial sphere) are visible to the unaided eye on a clear, dark night.

Stars are designated by one or more of the following naming systems:

- **Common Name:** Most names of stars, as now used, were given by the ancient Arabs and some by the Greeks or Romans. One of the stars of the Nautical Almanac, Nunki, was named by the Babylonians. Only a relatively few stars have names. Several of the stars on the daily pages of the almanacs had no name prior to 1953.

- **Bayer’s Name:** Most bright stars, including those with names, have been given a designation consisting of a Greek letter followed by the possessive form of the name of the constellation, such as α Cygni (Deneb, the brightest star in the constellation Cygnus, the swan). Roman letters are used when there are not enough Greek letters. Usually, the letters are assigned in order of brightness within the constellation; however, this is not always the case. For example, the letter designations of the stars in Ursa Major or the Big Dipper are assigned in order from the outer rim of the bowl to the end of the handle. This system of star designation was suggested by John Bayer of Augsburg, Germany, in 1603. All of the 173 stars included in the list near the back of the Nautical Almanac are listed by Bayer’s name, and, when applicable, their common name.

- **Flamsteed’s Number:** This system assigns numbers to stars in each constellation, from west to east in the order in which they cross the celestial meridian. An example is 95 Leonis, the 95th star in the constellation Leo. This system was suggested by John Flamsteed (1646-1719).

- **Catalog Number:** Stars are sometimes designated by the name of a star catalog and the number of the star as given in the catalog, such as A. G. Washington 632. In these catalogs, stars are listed in order from west to east, without regard to constellation, starting with the hour circle of the vernal equinox. This system is used primarily for fainter stars having no other designation. Navigators seldom have occasion to use this system.

1533. Star Charts

It is useful to be able to identify stars by relative position. A **star chart** (Figure 1533) is helpful in locating these relationships and others which may be useful. This method is limited to periods of relatively clear, dark skies with little or no overcast. Stars can also be identified by the Air Almanac **sky diagrams**, a **star finder**, *Pub. No. 249*, or by computation by hand or calculator.

Star charts are based upon the celestial equator system of coordinates, using declination and sidereal hour angle (or right ascension). The zenith of the observer is at the intersection of the parallel of declination equal to his latitude, and the hour circle coinciding with his celestial meridian. This hour circle has an SHA equal to 360° – LHA ♈ (or RA = LHA ♈). The horizon is everywhere 90° from the zenith. A **star globe** is similar to a terrestrial sphere, but with stars (and often constellations) shown instead of geographical positions. The Nautical Almanac includes instructions for using this

NAVIGATIONAL STARS AND THE PLANETS

Name	Pronunciation	Bayer name	Origin of name	Meaning of name	Distance*
Acamar	ā'kȧ·mąr	θ Eridani	Arabic	another form of Achernar	120
Achernar	ā'kĕr·nąr	α Eridani	Arabic	end of the river (Eridanus)	72
Acrux	ā'krŭks	α Crucis	Modern	coined from Bayer name	220
Adhara	ȧ·dā'rȧ	ε Canis Majoris	Arabic	the virgin(s)	350
Aldebaran	ăl dĕb'ȧ·rȧn	α Tauri	Arabic	follower (of the Pleiades)	64
Alioth	ăl'ĭ·ôth	ε Ursa Majoris	Arabic	another form of Capella	49
Alkaid	ăl·kād'	η Ursa Majoris	Arabic	leader of the daughters of the bier	190
Al Na'ir	ăl·nār'	α Gruis	Arabic	bright one (of the fish's tail)	90
Alnilam	ăl'nĭ·lăm	ε Orionis	Arabic	string of pearls	410
Alphard	ăl'fąrd	α Hydrae	Arabic	solitary star of the serpent	200
Alphecca	ăl·fĕk'ȧ	α Corona Borealis	Arabic	feeble one (in the crown)	76
Alpheratz	ăl·fē'răts	α Andromeda	Arabic	the horse's navel	120
Altair	ăl·tār'	α Aquilae	Arabic	flying eagle or vulture	16
Ankaa	ąn'ką	α Phoenicis	Arabic	coined name	93
Antares	ăn·tā'rēz	α Scorpii	Greek	rival of Mars (in color)	250
Arcturus	ąrk·tū'rŭs	α Bootis	Greek	the bear's guard	37
Atria	āt'rĭ·ȧ	α Trianguli Australis	Modern	coined from Bayer name	130
Avior	ā'vĭ·ôr	ε Carinae	Modern	coined name	350
Bellatrix	bĕ·lą'trĭks.	γ Orionis	Latin	female warrior	250
Betelgeuse	bĕt'ĕl·jūz	α Orionis	Arabic	the arm pit (of Orion)	300
Canopus	kȧ·nō'pŭs	α Carinae	Greek	city of ancient Egypt	230
Capella	kȧ·pĕl'ȧ	α Aurigae	Latin	little she-goat	46
Deneb	dĕn'ĕb	α Cygni	Arabic	tail of the hen	600
Denebola	dĕ·nĕb'ō·lȧ	β Leonis	Arabic	tail of the lion	42
Diphda	dĭf'dȧ	β Ceti	Arabic	the second frog (Fomalhaut was once the first)	57
Dubhe	dŭb'ē	α Ursa Majoris	Arabic	the bear's back	100
Elnath	ĕl'năth	β Tauri	Arabic	one butting with horns	130
Eltanin	ĕl·tā'nĭn	γ Draconis	Arabic	head of the dragon	150
Enif	ĕn'ĭf	ε Pegasi	Arabic	nose of the horse	250
Fomalhaut	fō'mȧl·ôt	α Piscis Austrini	Arabic	mouth of the southern fish	23
Gacrux	gā'krŭks	γ Crucis	Modern	coined from Bayer name	72
Gienah	jē'nȧ	γ Corvi	Arabic	right wing of the raven	136
Hadar	hā'dąr	β Centauri	Modern	leg of the centaur	200
Hamal	hăm'ȧl	α Arietis	Arabic	full-grown lamb	76
Kaus Australis	kôs ôs·trā'lĭs	ε Sagittarii	Ar., L.	southern part of the bow	163
Kochab	kō'kăb	β Ursa Minoris	Arabic	shortened form of "north star" (named when it was that, c. 1500 BC–AD 300)	100
Markab	mąr'kăb	α Pegasi	Arabic	saddle (of Pegasus)	100
Menkar	mĕn'kąr	α Ceti	Arabic	nose (of the whale)	1,100
Menkent	mĕn'kĕnt	θ Centauri	Modern	shoulder of the centaur	55
Miaplacidus	mī'ȧ·plăs'ĭ·dŭs	β Carinae	Ar., L.	quiet or still waters	86
Mirfak	mĭr'făk	α Persei	Arabic	elbow of the Pleiades	130
Nunki	nŭn'kē	σ Sagittarii	Bab.	constellation of the holy city (Eridu)	150
Peacock	pē'kŏk	α Pavonis	Modern	coined from English name of constellation	250
Polaris	pō·lā'rĭs	α Ursa Minoris	Latin	the pole (star)	450
Pollux	pŏl'ŭks	β Geminorum	Latin	Zeus' other twin son (Castor, α Geminorum, is first twin)	33
Procyon	prō'sĭ·ŏn	α Canis Minoris	Greek	before the dog (rising before the dog star, Sirius)	11
Rasalhague	rás'ąl·hā'gwē	α Ophiuchi	Arabic	head of the serpent charmer	67
Regulus	rĕg'ū·lŭs	α Leonis	Latin	the prince	67
Rigel	rī'jĕl	β Orionis	Arabic	foot (left foot of Orion)	500
Rigil Kentaurus	rī'jĭl kĕn·tô'rŭs	α Centauri	Arabic	foot of the centaur	4.3
Sabik	sā'bĭk	η Ophiuchi	Arabic	second winner or conqueror	69
Schedar	shĕd'ȧr	α Cassiopeiae	Arabic	the breast (of Cassiopeia)	360
Shaula	shô'lȧ	λ Scorpii	Arabic	cocked-up part of the scorpion's tail	200
Sirius	sĭr'ĭ·ŭs	α Canis Majoris	Greek	the scorching one (popularly, the dog star)	8.6
Spica	spī'kȧ	α Virginis	Latin	the ear of corn	155
Suhail	sōō·hāl'	λ Velorum	Arabic	shortened form of Al Suhail, one Arabic name for Canopus	200
Vega	vē'gȧ	α Lyrae	Arabic	the falling eagle or vulture	27
Zubenelgenubi	zōō·bĕn'ĕl·jĕ·nū'bē	α Librae	Arabic	southern claw (of the scorpion)	66

PLANETS

Name	Pronunciation	Origin of name	Meaning of name
Mercury	mûr'kū·rĭ	Latin	god of commerce and gain
Venus	vē'nŭs	Latin	goddess of love
Earth	ûrth	Mid. Eng.	—
Mars	märz	Latin	god of war
Jupiter	jōō'pĭ·tĕr	Latin	god of the heavens, identified with the Greek Zeus, chief of the Olympian gods
Saturn	săt'ĕrn	Latin	god of seed-sowing
Uranus	ū'rȧ·nŭs	Greek	the personification of heaven
Neptune	nĕp'tūn	Latin	god of the sea
Pluto	plōō'tō	Greek	god of the lower world (Hades)

Guide to pronunciations:
fāte, ădd, finȧl, lȧst, ȧbound, ärm; bē, ĕnd, camĕl, readĕr; īce, bĭt, anĭmal; ōver, pōetic, hŏt, lôrd, mōōn; tūbe, ūnite, tŭb, circŭs, ûrn

*Distances in light-years. One light-year equals approximately 63,300 AU, or 5,880,000,000,000 miles. Authorities differ on distances of the stars; the values given are representative.

Figure 1531a. Navigational stars and the planets.

CONSTELLATIONS

Name	Pronunciation	Genitive	Pronunciation	Meaning	Navigational stars or approximate position
Hydra*	hī′drȧ	Hydrae	hī′drē	water monster	Alphard
Hydrus	hī′drŭs	Hydri	hī′drī	water snake	d 70°S, SHA 320°
Indus	ĭn′dŭs	Indi	ĭn′dī	Indian	d 60°S, SHA 35°
Lacerta	lȧ·sûr′tȧ	Lacertae	lȧ·sŭr′tē	lizard	d 45°N, SHA 25°
Leo (♌)*	lē′ō	Leonis	lḗ·ō′nĭs	lion	Denebola, Regulus
Leo Minor	lē′ō mī′nẽr	Leonis Minoris	lḗ·ō′nĭs mĭ·nō′rĭs	smaller lion	d 35°N, SHA 205°
Lepus*	lē′pŭs	Leporis	lĕp′ŏ·rĭs	hare	d 20°S, SHA 275°
Libra (♎)*	lī′brȧ	Librae	lī′brē	balance [scales]†	Zubenelgenubi
Lupus*	lū′pŭs	Lupi	lū′pī	wolf	d 45°S, SHA 130°
Lynx	lĭngks	Lyncis	lĭn′sĭs	lynx	d 50°N, SHA 240°
Lyra*	lī′rȧ	Lyrae	lī′rē	lyre	Vega
Mensa	mĕn′sȧ	Mensae	mĕn′sē	table (mountain)††	d 75°S, SHA 275°
Microscopium	mī′krṓ·skō′pĭ·ŭm	Microscopii	mī′krṓ·skō′pĭ·ī	microscope	d 35°S, SHA 45°
Monoceros	mṓ·nŏs′ẽr·ŏs	Monocerotis	mṓ·nŏs′ẽr·ō′tĭs	unicorn	d 0°, SHA 255°
Musca	mŭs′kȧ	Muscae	mŭs′sē	fly	d 70°S, SHA 175°
Norma	nôr′mȧ	Normae	nôr′mē	square (and rule)††	d 50°S, SHA 120°
Octans	ŏk′tănz	Octantis	ŏk·tăn′tĭs	octant	d 85°S, SHA 40°
Ophiuchus*	ŏf′ĭ·ū′kŭs	Ophiuchi	ŏf′ĭ·ū′kī	serpent holder	Rasalhague, Sabik
Orion*	ṓ·rī′ŏn	Orionis	ō′rĭ·ō′nĭs	Orion [the hunter]†	Alnilam, Bellatrix, Betelgeuse, Rigel
Pavo	pā′vō	Pavonis	pȧ·vō′nĭs	peacock	Peacock
Pegasus*	pĕg′ȧ·sŭs	Pegasi	pĕg′ȧ·sī	Pegasus [winged horse]†	Enif, Markab
Perseus*	pûr′sūs	Persei	pûr′sḗ·ī	Perseus [mythological character]†	Mirfak
Phoenix	fē′nĭks	Phoenicis	fḗ·nī′sĭs	phoenix [the immortal bird]†	Ankaa
Pictor	pĭk′tẽr	Pictoris	pĭk·tō′rĭs	painter (easel of)††	d 55°S, SHA 275°
Pisces (♓)*	pĭs′ēz	Piscium	pĭsh′ĭ·ŭm	fishes	d 15°N, SHA 355°
Piscis Austrinus*	pĭs′ĭs ôs·trī′nŭs	Piscis Austrini	pĭs′ĭs ôs·trī′nī	southern fish	Fomalhaut
Puppis**	pŭp′ĭs	Puppis	pŭp′ĭs	stern [of ship]†	d 30°S, SHA 245°
Pyxis**	pĭk′sĭs	Pyxidis	pĭk′sĭ·dĭs	mariner's compass	d 25°S, SHA 230°
Reticulum	rḗ·tĭk′ṻ·lŭm	Reticuli	rḗ·tĭk′ṻ·lī	net	d 60°S, SHA 300°
Sagitta*	sȧ·jĭt′ȧ	Sagittae	sȧ·jĭt′ē	arrow	d 20°N, SHA 65°
Sagittarius (♐)*	săj′ĭ·tā′rĭ·ŭs	Sagittarii	săj′ĭ·tā′rĭ·ī	archer	Kaus Australis, Nunki
Scorpius (♏)*	skôr′pĭ·ŭs	Scorpii	skôr′pĭ·ī	scorpion	Antares, Shaula
Sculptor	skŭlp′tẽr	Sculptoris	skŭlp·tō′rĭs	sculptor (workshop of)††	d 30°S, SHA 355°
Scutum	skū′tŭm	Scuti	skū′tī	shield	d 10°S, SHA 80°
Serpens*	sûr′pĕnz	Serpentis	sẽr·pĕn′tĭs	serpent	d 10°N, SHA 125°
Sextans	sĕks′tănz	Sextantis	sĕks·tăn′tĭs	sextant	d 0°, SHA 205°
Taurus (♉)*	tô′rŭs	Tauri	tô′rī	bull	Aldebaran, Elnath
Telescopium	tĕl′ḗ·skō′pĭ·ŭm	Telescopii	tĕl′ḗ·skō′pĭ·ī	telescope	d 50°S, SHA 75°
Triangulum*	trī·ăng′gṻ·lŭm	Trianguli	trī·ăng′gṻ·lī	triangle	d 30°N, SHA 330°
Triangulum Australe	trī·ăng′gṻ·lŭm ôs·trā′lē	Trianguli Australis	trī·ăng′gṻ·lī ôs·trā′lĭs	southern triangle	Atria
Tucana	tṻ·kā′nȧ	Tucanae	tṻ·kā′nē	toucan [a bird]†	d 65°S, SHA 5°
Ursa Major*	ûr′sȧ mā′jẽr	Ursae Majoris	ûr′sē mā·jō′rĭs	larger bear	Alioth, Alkaid, Dubhe
Ursa Minor*	ûr′sȧ mī′nẽr	Ursae Minoris	ûr′sē mĭ·nō′rĭs	smaller bear	Kochab, Polaris
Vela**	vē′lȧ	Velorum	vḗ·lō′rŭm	sails	Suhail
Virgo (♍)*	vûr′gō	Virginis	vûr′jĭ·nĭs	virgin	Spica
Volans	vō′lănz	Volantis	vṓ lăn′tĭs	flying (fish)††	d 70°S, SHA 240°
Vulpecula	vŭl·pĕk′ṻ·lȧ	Vulpeculae	vŭl·pĕk′ṻ·lē	little fox	d 25°N, SHA 60°

Zodiacal constellations are given in bold type, with their symbols.
*One of the original constellations of Ptolemy.
**Part of the single constellation Argo Navis of Ptolemy.
†Parts within brackets are amplifications of the meanings of constellation names.
††Parts within parentheses are the meanings of words deleted from former, more complete constellation names.

Guide to pronunciations:

fāte, cāre, hăt, finăl, ȧbound, sofȧ, ärm; bē, crḗate, ĕnd, readẽr; īce, bĭt; ōver, pṓetic, hŏt, cŏnnect, lôrd, mōōn; tūbe, ṻnite, tŭb, circŭs, ûrn.

Figure 1531b. Constellations.

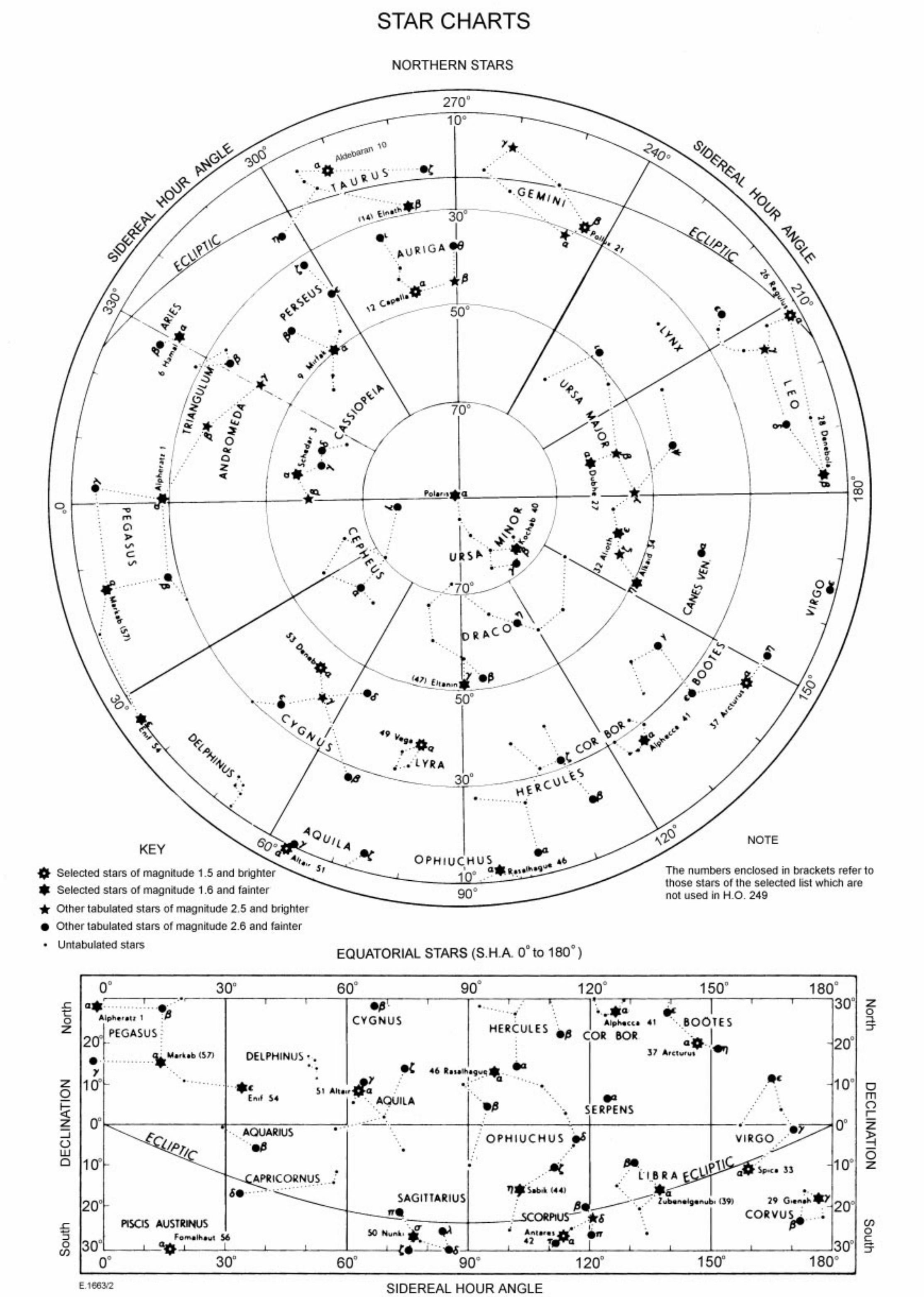


Figure 1533. Star chart.

device. On a star globe the celestial sphere is shown as it would appear to an observer outside the sphere. Constellations appear reversed. Star charts may show a similar view, but more often they are based upon the view from inside the sphere, as seen from the earth. On these charts, north is at the top, as with maps, but east is to the left and west to the right. The directions seem correct when the chart is held overhead, with the top toward the north, so the relationship is similar to the sky.

The Nautical Almanac has four star charts. The two principal ones are on the polar azimuthal equidistant projection, one centered on each celestial pole. Each chart extends from its pole to declination 10° (same name as pole). Below each polar chart is an auxiliary chart on the Mercator projection, from 30°N to 30°S. On any of these charts, the zenith can be located as indicated, to determine which stars are overhead. The horizon is 90° from the zenith. The charts can also be used to determine the location of a star relative to surrounding stars.

The Air Almanac contains a folded chart on the rectangular projection. This projection is suitable for indicating the coordinates of the stars, but excessive distortion occurs in regions of high declination. The celestial poles are represented by the top and bottom horizontal lines the same length as the celestial equator. To locate the horizon on this chart, first locate the zenith as indicated above, and then locate the four cardinal points. The north and south points are 90° from the zenith, along the celestial meridian. The distance to the elevated pole (having the same name as the latitude) is equal to the colatitude of the observer. The remainder of the 90° (the latitude) is measured from the same pole, along the lower branch of the celestial meridian, 180° from the upper branch containing the zenith. The east and west points are on the celestial equator at the hour circle 90° east and west (or 90° and 270° in the same direction) from the celestial meridian. The horizon is a sine curve through the four cardinal points. Directions on this projection are distorted.

The star charts shown in Figure 1534 through Figure 1537, on the transverse Mercator projection, are designed to assist in learning Polaris and the stars listed on the daily pages of the Nautical Almanac. Each chart extends about 20° beyond each celestial pole, and about 60° (four hours) each side of the central hour circle (at the celestial equator). Therefore, they do not coincide exactly with that half of the celestial sphere above the horizon at any one time or place. The zenith, and hence the horizon, varies with the position of the observer on the earth. It also varies with the rotation of the earth (apparent rotation of the celestial sphere). The charts show all stars of fifth magnitude and brighter as they appear in the sky, but with some distortion toward the right and left edges.

The overprinted lines add certain information of use in locating the stars. Only Polaris and the 57 stars listed on the daily pages of the Nautical Almanac are named on the charts. The almanac star charts can be used to locate the additional stars given near the back of the Nautical Almanac and the Air Almanac. Dashed lines connect stars of some of the more prominent constellations. Solid lines indicate the celestial equator and useful relationships among stars in different constellations. The celestial poles are marked by crosses, and labeled. By means of the celestial equator and the poles, one can locate his zenith approximately along the mid hour circle, when this coincides with his celestial meridian, as shown in the table below. At any time earlier than those shown in the table the zenith is to the right of center, and at a later time it is to the left, approximately one-quarter of the distance from the center to the outer edge (at the celestial equator) for each hour that the time differs from that shown. The stars in the vicinity of the North Pole can be seen in proper perspective by inverting the chart, so that the zenith of an observer in the Northern Hemisphere is up from the pole.

1534. Stars In The Vicinity Of Pegasus

In autumn the evening sky has few first magnitude stars. Most are near the southern horizon of an observer in the latitudes of the United States. A relatively large number of second and third magnitude stars seem conspicuous, perhaps because of the small number of brighter stars. High in the southern sky three third magnitude stars and one second magnitude star form a square with sides nearly 15° of arc in length. This is Pegasus, the winged horse.

	Fig. 1534	Fig.1535	Fig. 1536	Fig. 1537
Local sidereal time	0000	0600	1200	1800
LMT 1800	Dec. 21	Mar. 22	June 22	Sept. 21
LMT 2000	Nov. 21	Feb. 20	May 22	Aug. 21
LMT 2200	Oct. 21	Jan. 20	Apr. 22	July 22
LMT 0000	Sept. 22	Dec. 22	Mar. 23	June 22
LMT 0200	Aug. 22	Nov. 22	Feb. 21	May 23
LMT 0400	July 23	Oct. 22	Jan 21	Apr. 22
LMT 0600	June 22	Sept. 21	Dec. 22	Mar. 23

Table 1533. Locating the zenith on the star diagrams.

Only Markab at the southwestern corner and Alpheratz

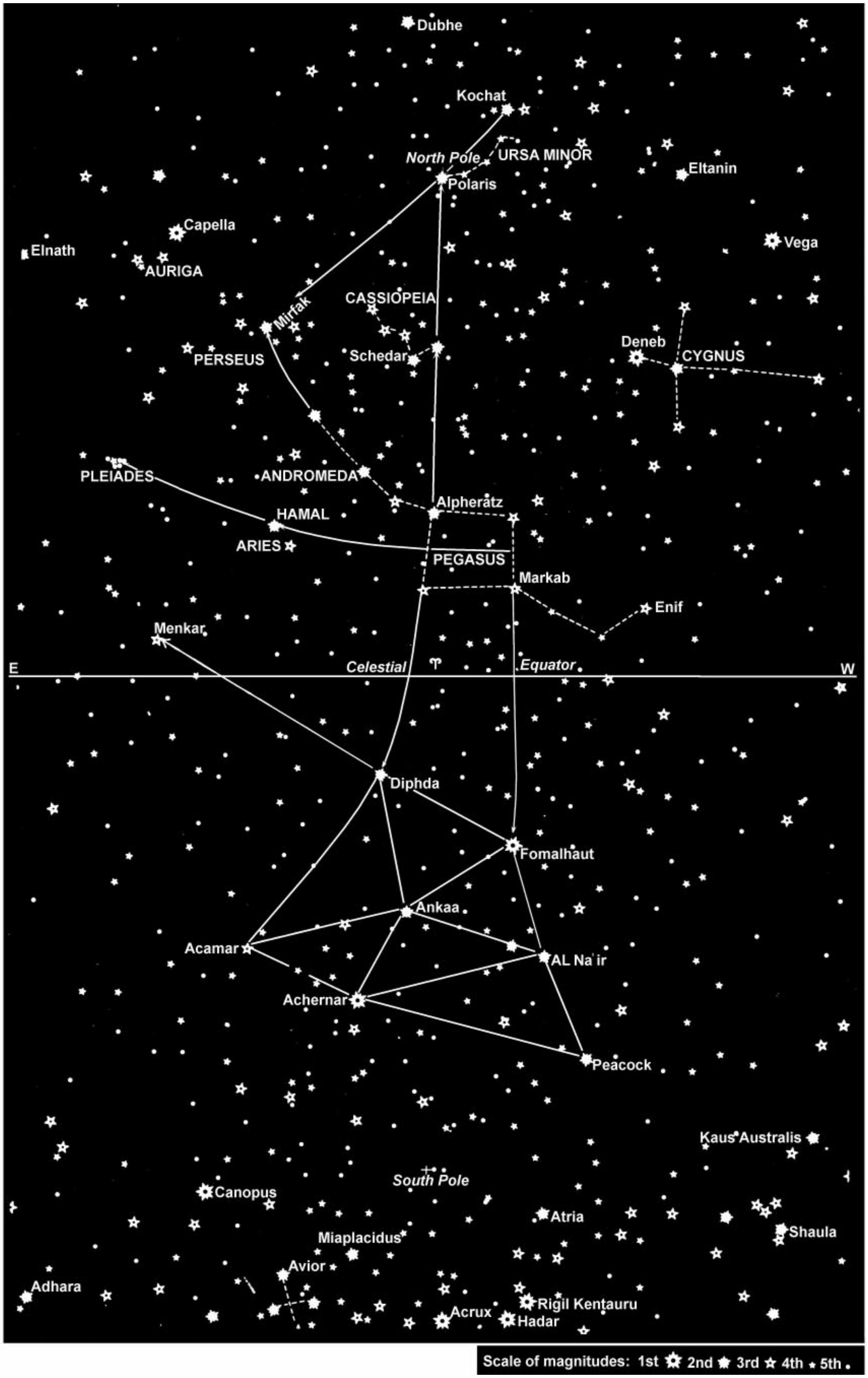


Figure 1534. Stars in the vicinity of Pegasus.

at the northeastern corner are listed on the daily pages of the Nautical Almanac. Alpheratz is part of the constellation Andromeda, the princess, extending in an arc toward the northeast and terminating at Mirfak in Perseus, legendary rescuer of Andromeda.

A line extending northward through the eastern side of the square of Pegasus passes through the leading (western) star of M-shaped (or W-shaped) Cassiopeia, the legendary mother of the princess Andromeda. The only star of this constellation listed on the daily pages of the Nautical Almanac is Schedar, the second star from the leading one as the configuration circles the pole in a counterclockwise direction. If the line through the eastern side of the square of Pegasus is continued on toward the north, it leads to second magnitude Polaris, the North Star (less than 1° from the north celestial pole) and brightest star of Ursa Minor, the Little Dipper. Kochab, a second magnitude star at the other end of Ursa Minor, is also listed in the almanacs. At this season Ursa Major is low in the northern sky, below the celestial pole. A line extending from Kochab through Polaris leads to Mirfak, assisting in its identification when Pegasus and Andromeda are near or below the horizon.

Deneb, in Cygnus, the swan, and Vega are bright, first magnitude stars in the northwestern sky.

The line through the eastern side of the square of Pegasus approximates the hour circle of the vernal equinox, shown at Aries on the celestial equator to the south. The sun is at Aries on or about March 21, when it crosses the celestial equator from south to north. If the line through the eastern side of Pegasus is extended southward and curved slightly toward the east, it leads to second magnitude Diphda. A longer and straighter line southward through the western side of Pegasus leads to first magnitude Fomalhaut. A line extending northeasterly from Fomalhaut through Diphda leads to Menkar, a third magnitude star, but the brightest in its vicinity. Ankaa, Diphda, and Fomalhaut form an isosceles triangle, with the apex at Diphda. Ankaa is near or below the southern horizon of observers in latitudes of the United States. Four stars farther south than Ankaa may be visible when on the celestial meridian, just above the horizon of observers in latitudes of the extreme southern part of the United States. These are Acamar, Achernar, Al Na'ir, and Peacock. These stars, with each other and with Ankaa, Fomalhaut, and Diphda, form a series of triangles as shown in Figure 1534. Almanac stars near the bottom of Figure 1534 are discussed in succeeding articles.

Two other almanac stars can be located by their positions relative to Pegasus. These are Hamal in the constellation Aries, the ram, east of Pegasus, and Enif, west of the southern part of the square, identified in Figure 1534. The line leading to Hamal, if continued, leads to the Pleiades (the Seven Sisters), not used by navigators for celestial observations, but a prominent figure in the sky, heralding the approach of the many conspicuous stars of the winter evening sky.

1535. Stars In The Vicinity Of Orion

As Pegasus leaves the meridian and moves into the western sky, Orion, the hunter, rises in the east. With the possible exception of Ursa Major, no other configuration of stars in the entire sky is as well known as Orion and its immediate surroundings. In no other region are there so many first magnitude stars.

The belt of Orion, nearly on the celestial equator, is visible in virtually any latitude, rising and setting almost on the prime vertical, and dividing its time equally above and below the horizon. Of the three second magnitude stars forming the belt, only Alnilam, the middle one, is listed on the daily pages of the Nautical Almanac.

Four conspicuous stars form a box around the belt. Rigel, a hot, blue star, is to the south. Betelgeuse, a cool, red star lies to the north. Bellatrix, bright for a second magnitude star but overshadowed by its first magnitude neighbors, is a few degrees west of Betelgeuse. Neither the second magnitude star forming the southeastern corner of the box, nor any star of the dagger, is listed on the daily pages of the Nautical Almanac.

A line extending eastward from the belt of Orion, and curving toward the south, leads to Sirius, the brightest star in the entire heavens, having a magnitude of –1.6. Only Mars and Jupiter at or near their greatest brilliance, the sun, moon, and Venus are brighter than Sirius. Sirius is part of the constellation Canis Major, the large hunting dog of Orion. Starting at Sirius a curved line extends northward through first magnitude Procyon, in Canis Minor, the small hunting dog; first magnitude Pollux and second magnitude Castor (not listed on the daily pages of the Nautical Almanac), the twins of Gemini; brilliant Capella in Auriga, the charioteer; and back down to first magnitude Aldebaran, the follower, which trails the Pleiades, the seven sisters. Aldebaran, brightest star in the head of Taurus, the bull, may also be found by a curved line extending northwestward from the belt of Orion. The V-shaped figure forming the outline of the head and horns of Taurus points toward third magnitude Menkar. At the summer solstice the sun is between Pollux and Aldebaran.

If the curved line from Orion's belt southeastward to Sirius is continued, it leads to a conspicuous, small, nearly equilateral triangle of three bright second magnitude stars of nearly equal brilliancy. This is part of Canis Major. Only Adhara, the westernmost of the three stars, is listed on the daily pages of the Nautical Almanac. Continuing on with somewhat less curvature, the line leads to Canopus, second brightest star in the heavens and one of the two stars having a negative magnitude (–0.9). With Suhail and Miaplacidus, Canopus forms a large, equilateral triangle which partly encloses the group of stars often mistaken for Crux. The brightest star within this triangle is Avior, near its center. Canopus is also at one apex of a triangle formed with Adhara to the north and Suhail to the east, another triangle with Acamar to the west and Achernar to the southwest, and an-

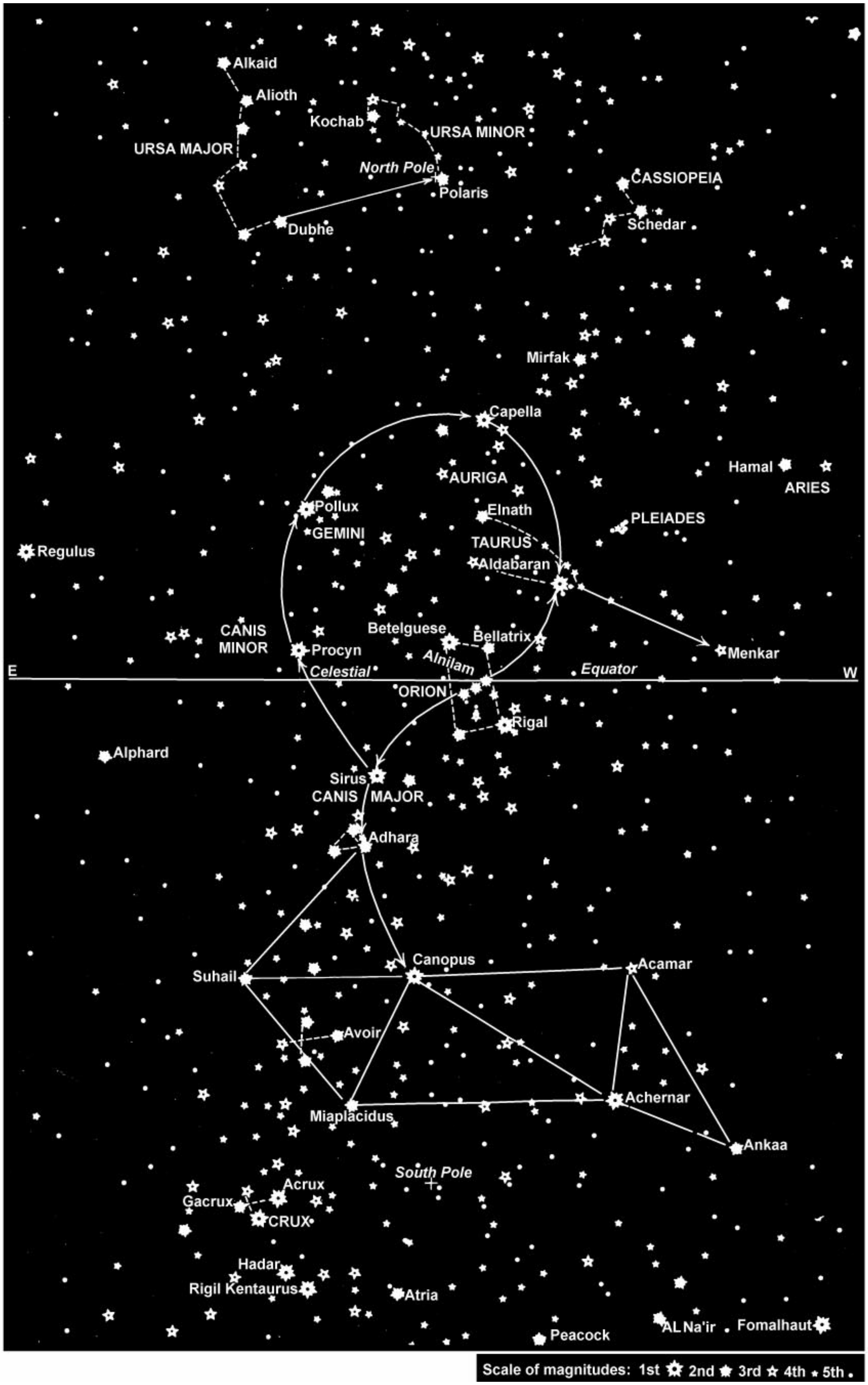


Figure 1535. Stars in the vicinity of Orion.

other with Achernar and Miaplacidus. Acamar, Achernar, and Ankaa form still another triangle toward the west. Because of chart distortion, these triangles do not appear in the sky in exactly the relationship shown on the star chart. Other daily-page almanac stars near the bottom of Figure 1535 are discussed in succeeding articles.

In the winter evening sky, Ursa Major is east of Polaris, Ursa Minor is nearly below it, and Cassiopeia is west of it. Mirfak is northwest of Capella, nearly midway between it and Cassiopeia. Hamal is in the western sky. Regulus and Alphard are low in the eastern sky, heralding the approach of the configurations associated with the evening skies of spring.

1536. Stars In The Vicinity Of Ursa Major

As if to enhance the splendor of the sky in the vicinity of Orion, the region toward the east, like that toward the west, has few bright stars, except in the vicinity of the south celestial pole. However, as Orion sets in the west, leaving Capella and Pollux in the northwestern sky, a number of good navigational stars move into favorable positions for observation.

Ursa Major, the great bear, appears prominently above the north celestial pole, directly opposite Cassiopeia, which appears as a "W" just above the northern horizon of most observers in latitudes of the United States. Of the seven stars forming Ursa Major, only Dubhe, Alioth, and Alkaid are listed on the daily pages of the Nautical Almanac.

The two second magnitude stars forming the outer part of the bowl of Ursa Major are often called the pointers because a line extending northward (down in spring evenings) through them points to Polaris. Ursa Minor, the Little Bear, contains Polaris at one end and Kochab at the other. Relative to its bowl, the handle of Ursa Minor curves in the opposite direction to that of Ursa Major.

A line extending southward through the pointers, and curving somewhat toward the west, leads to first magnitude Regulus, brightest star in Leo, the lion. The head, shoulders, and front legs of this constellation form a sickle, with Regulus at the end of the handle. Toward the east is second magnitude Denebola, the tail of the lion. On toward the southwest from Regulus is second magnitude Alphard, brightest star in Hydra, the sea serpent. A dark sky and considerable imagination are needed to trace the long, winding body of this figure.

A curved line extending the arc of the handle of Ursa Major leads to first magnitude Arcturus. With Alkaid and Alphecca, brightest star in Corona Borealis, the Northern Crown, Arcturus forms a large, inconspicuous triangle. If the arc through Arcturus is continued, it leads next to first magnitude Spica and then to Corvus, the crow. The brightest star in this constellation is Gienah, but three others are nearly as bright. At autumnal equinox, the sun is on the celestial equator, about midway between Regulus and Spica.

A long, slightly curved line from Regulus, east-southeasterly through Spica, leads to Zubenelgenubi at the southwestern corner of an inconspicuous box-like figure called Libra, the scales.

Returning to Corvus, a line from Gienah, extending diagonally across the figure and then curving somewhat toward the east, leads to Menkent, just beyond Hydra.

Far to the south, below the horizon of most northern hemisphere observers, a group of bright stars is a prominent feature of the spring sky of the Southern Hemisphere. This is Crux, the Southern Cross. Crux is about 40° south of Corvus. The "false cross" to the west is often mistaken for Crux. Acrux at the southern end of Crux and Gacrux at the northern end are listed on the daily pages of the Nautical Almanac.

The triangles formed by Suhail, Miaplacidus, and Canopus, and by Suhail, Adhara, and Canopus, are west of Crux. Suhail is in line with the horizontal arm of Crux. A line from Canopus, through Miaplacidus, curved slightly toward the north, leads to Acrux. A line through the east-west arm of Crux, eastward and then curving toward the south, leads first to Hadar and then to Rigil Kentaurus, both very bright stars. Continuing on, the curved line leads to small Triangulum Australe, the Southern Triangle, the easternmost star of which is Atria.

1537. Stars In The Vicinity Of Cygnus

As the celestial sphere continues in its apparent westward rotation, the stars familiar to a spring evening observer sink low in the western sky. By midsummer, Ursa Major has moved to a position to the left of the north celestial pole, and the line from the pointers to Polaris is nearly horizontal. Ursa Minor, is standing on its handle, with Kochab above and to the left of the celestial pole. Cassiopeia is at the right of Polaris, opposite the handle of Ursa Major.

The only first magnitude star in the western sky is Arcturus, which forms a large, inconspicuous triangle with Alkaid, the end of the handle of Ursa Major, and Alphecca, the brightest star in Corona Borealis, the Northern Crown.

The eastern sky is dominated by three very bright stars. The westernmost of these is Vega, the brightest star north of the celestial equator, and third brightest star in the heavens, with a magnitude of 0.1. With a declination of a little less than 39°N, Vega passes through the zenith along a path across the central part of the United States, from Washington in the east to San Francisco on the Pacific coast. Vega forms a large but conspicuous triangle with its two bright neighbors, Deneb to the northeast and Altair to the southeast. The angle at Vega is nearly a right angle. Deneb is at the end of the tail of Cygnus, the swan. This configuration is sometimes called the Northern Cross, with Deneb at the head. To modern youth it more nearly resembles a dive bomber, while it is still well toward the east, with Deneb at the nose of the fuselage. Altair has two fainter stars close by, on opposite sides. The line formed by Altair and its two fainter companions, if extended in a northwesterly direction, passes through Vega, and on to second magnitude Eltanin. The angular distance from Vega to Eltanin is about half that from Altair to Vega. Vega and Altair,

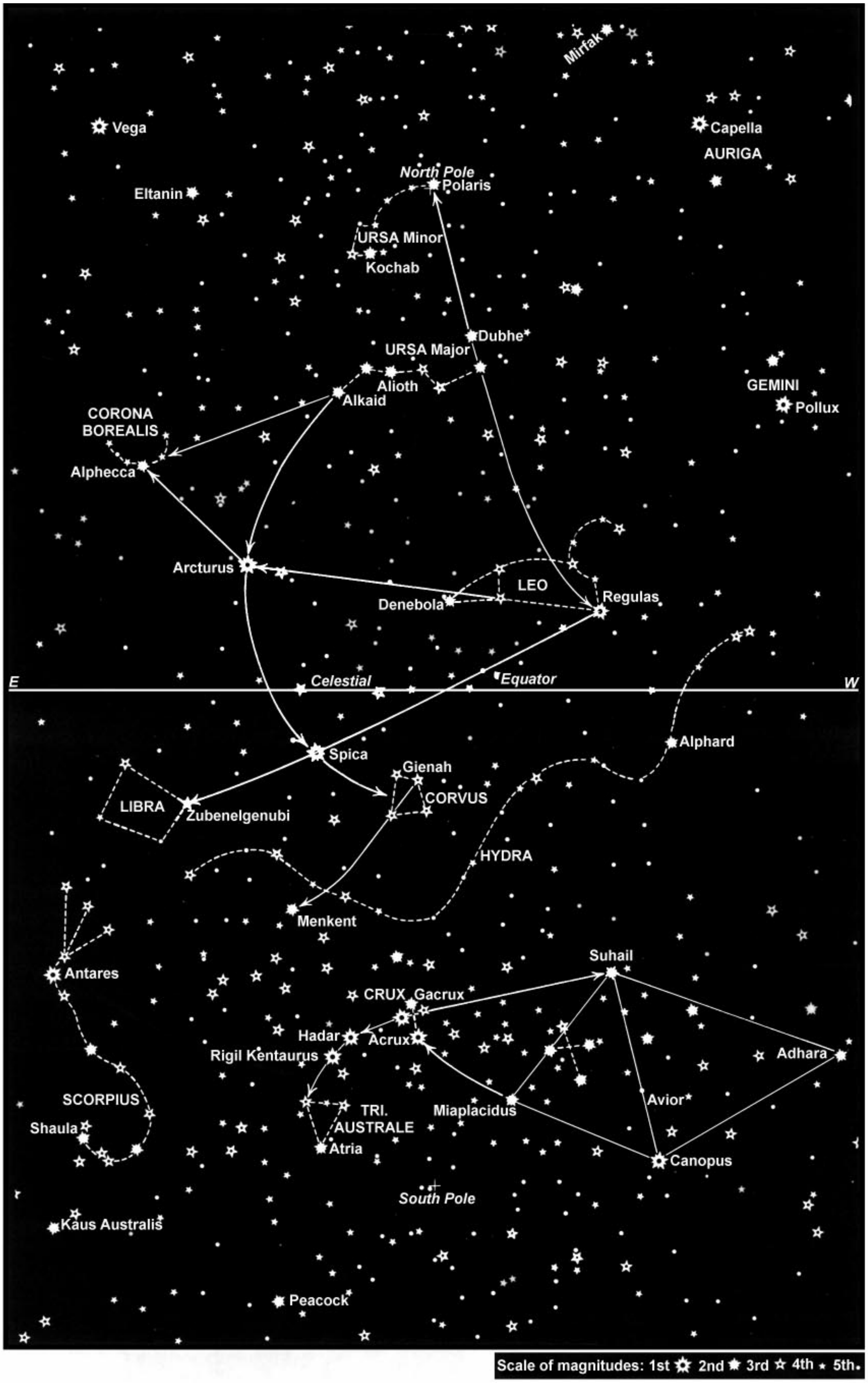


Figure 1536. Stars in the vicinity of Ursa Major.

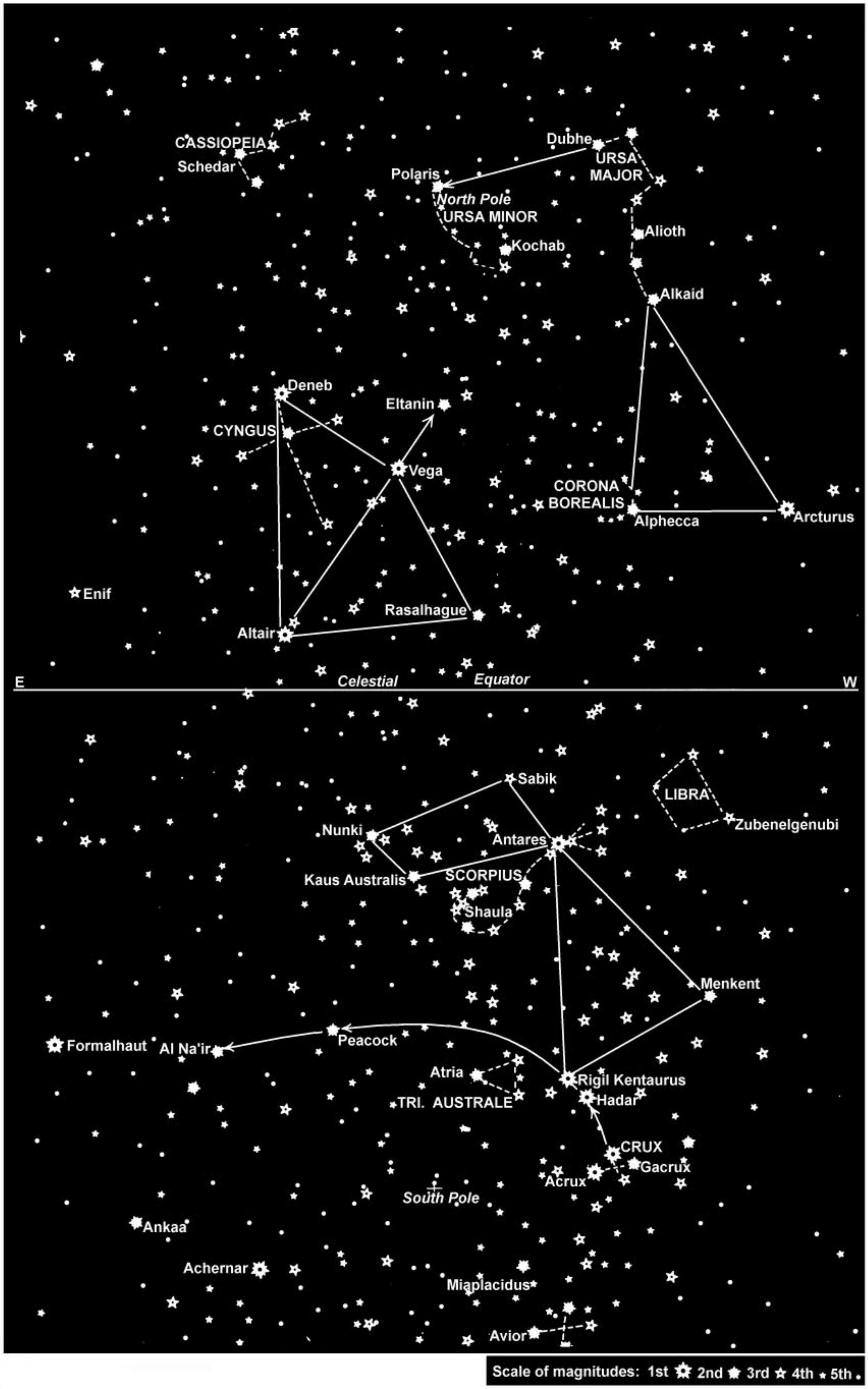


Figure 1537. Stars in the vicinity of Cygnus.

with second magnitude Rasalhague to the west, form a large equilateral triangle. This is less conspicuous than the Vega-Deneb-Altair triangle because the brilliance of Rasalhague is much less than that of the three first magnitude stars, and the triangle is overshadowed by the brighter one.

Far to the south of Rasalhague, and a little toward the west, is a striking configuration called Scorpius, the scorpion. The brightest star, forming the head, is red Antares. At the tail is Shaula.

Antares is at the southwestern corner of an approximate parallelogram formed by Antares, Sabik, Nunki, and Kaus Australis. With the exception of Antares, these stars are only slightly brighter than a number of others nearby, and so this parallelogram is not a striking figure. At winter solstice the sun is a short distance northwest of Nunki.

Northwest of Scorpius is the box-like Libra, the scales, of which Zubenelgenubi marks the southwest corner.

With Menkent and Rigil Kentaurus to the southwest, Antares forms a large but unimpressive triangle. For most observers in the latitudes of the United States, Antares is low in the southern sky, and the other two stars of the triangle are below the horizon. To an observer in the Southern Hemisphere Crux is to the right of the south celestial pole, which is not marked by a conspicuous star. A long, curved line, starting with the now-vertical arm of Crux and extending northward and then eastward, passes successively through Hadar, Rigil Kentaurus, Peacock, and Al Na'ir.

Fomalhaut is low in the southeastern sky of the southern hemisphere observer, and Enif is low in the eastern sky at nearly any latitude. With the appearance of these stars it is not long before Pegasus will appear over the eastern horizon during the evening, and as the winged horse climbs evening by evening to a position higher in the sky, a new annual cycle approaches.

1538. Planet Diagram

The planet diagram in the Nautical Almanac shows, in graphical form for any date during the year, the LMT of meridian passage of the sun, for the five planets Mercury, Venus, Mars, Jupiter, and Saturn, and of each 30° of SHA. The diagram provides a general picture of the availability of planets and stars for observation, and thus shows:

1. Whether a planet or star is too close to the sun for observation.
2. Whether a planet is a morning or evening star.
3. Some indication of the planet's position during twilight.
4. The proximity of other planets.
5. Whether a planet is visible from evening to morning twilight.

A band 45^m wide is shaded on each side of the curve marking the LMT of meridian passage of the sun. Any planet and most stars lying within the shaded area are too close to the sun for observation.

When the meridian passage occurs at midnight, the body is in opposition to the sun and is visible all night; planets may be observable in both morning and evening twilights. As the time of meridian passage decreases, the body ceases to be observable in the morning, but its altitude above the eastern horizon during evening twilight gradually increases; this continues until the body is on the meridian at twilight. From then onwards the body is observable above the western horizon and its altitude at evening twilight gradually decreases; eventually the body comes too close to the sun for observation. When the body again becomes visible, it is seen as a morning star low in the east. Its altitude at twilight increases until meridian passage occurs at the time of morning twilight. Then, as the time of meridian passage decreases to 0^h, the body is observable in the west in the morning twilight with a gradually decreasing altitude, until it once again reaches opposition.

Only about one-half the region of the sky along the ecliptic, as shown on the diagram, is above the horizon at one time. At sunrise (LMT about 6^h) the sun and, hence, the region near the middle of the diagram, are rising in the east; the region at the bottom of the diagram is setting in the west. The region half way between is on the meridian. At sunset (LMT about 18^h) the sun is setting in the west; the region at the top of the diagram is rising in the east. Marking the planet diagram of the Nautical Almanac so that east is at the top of the diagram and west is at the bottom can be useful to interpretation.

If the curve for a planet intersects the vertical line connecting the date graduations below the shaded area, the planet is a morning star; if the intersection is above the shaded area, the planet is an evening star.

A similar planet location diagram in the Air Almanac represents the region of the sky along the ecliptic within which the sun, moon, and planets always move; it shows, for each date, the sun in the center and the relative positions of the moon, the five planets Mercury, Venus, Mars, Jupiter, Saturn and the four first magnitude stars Aldebaran, Antares, Spica, and Regulus, and also the position on the ecliptic which is north of Sirius (i.e. Sirius is 40° south of this point). The first point of Aries is also shown for reference. The magnitudes of the planets are given at suitable intervals along the curves. The moon symbol shows the correct phase. A straight line joining the date on the left-hand side with the same date of the right-hand side represents a complete circle around the sky, the two ends of the line representing the point 180° from the sun; the intersections with the curves show the spacing of the bodies along the ecliptic on the date. The time scale indicates roughly the local mean time at which an object will be on the observer's meridian.

At any time only about half the region on the diagram is above the horizon. At sunrise the sun (and hence the region near the middle of the diagram), is rising in the east and the region at the end marked "West" is setting in the west; the region half-way between these extremes is on the meridian, as will be indicated by the local time (about 6^h). At the time

of sunset (local time about 18^h) the sun is setting in the west, and the region at the end marked “East” is rising in the east.

The diagram should be used in conjunction with the Sky Diagrams.

1539. Star Finders

Various devices have been devised to help an observer find individual stars. The most widely used is the **Star Finder and Identifier**, formerly published by the U.S. Navy Hydrographic Office, and now published commercially. The current model, No. 2102D, as well as the previous 2102C model, patented by E. B. Collins, employs the same basic principle as that used in the Rude Star Finder patented by Captain G. T. Rude, USC&GS, and later sold to the Hydrographic Office. Successive models reflect various modifications to meet changing conditions and requirements.

The star base of No. 2102D consists of a thin, white, opaque, plastic disk about 8 $^1/_2$ inches in diameter, with a small peg in the center. On one side the north celestial pole is shown at the center, and on the opposite side the south celestial pole is at the center. All of the stars listed on the daily pages of the Nautical Almanac are shown on a polar azimuthal equidistant projection extending to the opposite pole. The south pole side is shown in Figure 1539a. Many copies of an older edition, No. 2102C, showing the stars listed in the almanacs prior to 1953, and having other minor differences, are still in use. These are not rendered obsolete by the newer edition, but should be corrected by means of the current almanac. The rim of each side is graduated to half a degree of LHA ♈ (or 360° – SHA).

Ten transparent templates of the same diameter as the star base are provided. There is one template for each 10° of latitude, labeled 5°, 15°, 25°, etc., plus a 10th (printed in red) showing meridian angle and declination. The older edition (No. 2102C) did not have the red meridian angle-declination template. Each template can be used on either

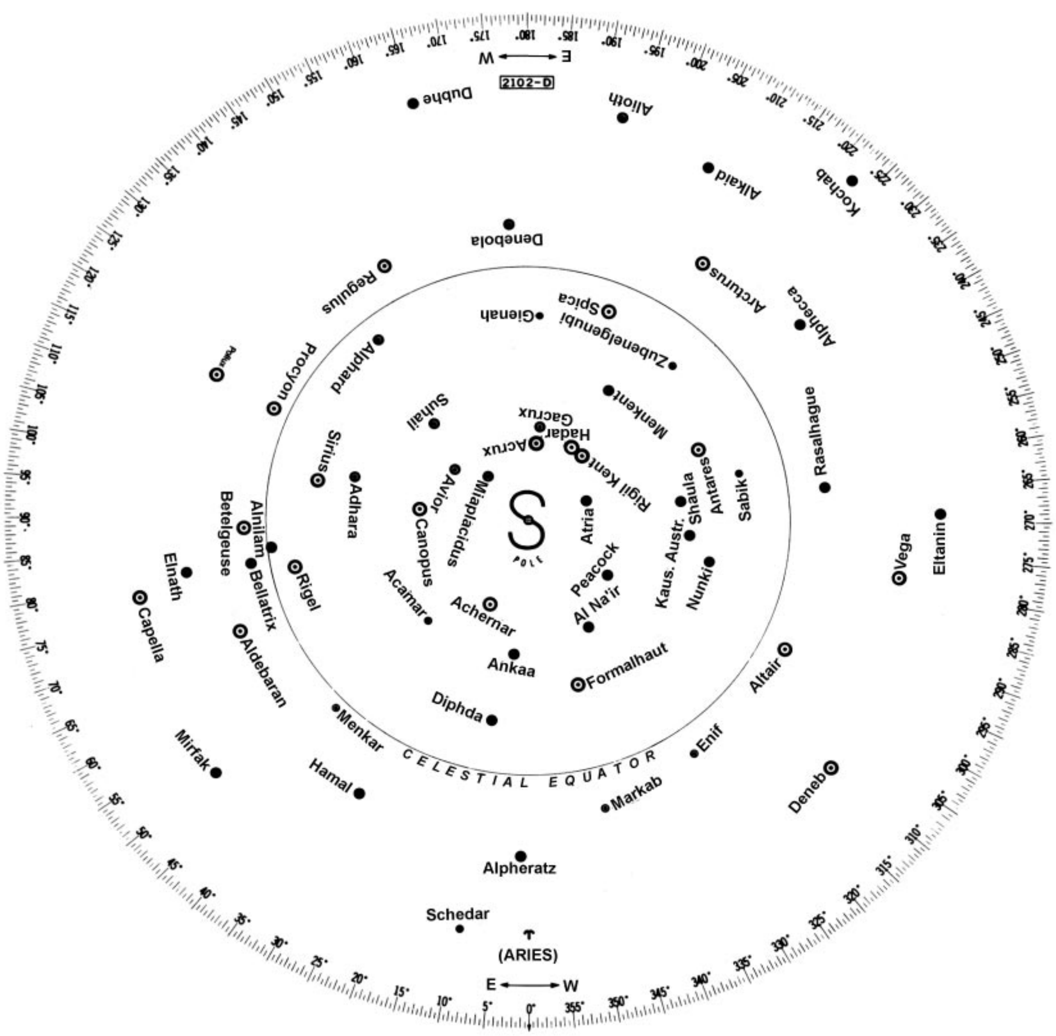


Figure 1539a. The south pole side of the star base of No. 2102D.

side of the star base, being centered by placing a small center hole in the template over the center peg of the star base. Each latitude template has a family of altitude curves at 5° intervals from the horizon (from altitude 10° on the older No. 2102C) to 80°. A second family of curves, also at 5° intervals, indicates azimuth. The north-south azimuth line is the celestial meridian. The star base, templates, and a set of instructions are kept in a circular leatherette container.

Since the sun, moon, and planets continually change apparent position relative to the “fixed” stars, they are not shown on the star base. However, their positions at any time, as well as the positions of additional stars, can be plotted. To do this, determine 360° – SHA of the body. For the stars and planets, SHA is listed in the Nautical Almanac. For the sun and moon, 360° – SHA is found by subtracting GHA of the body from GHA ♈ at the same time. Locate 360° – SHA on the scale around the rim of the star base. A straight line from this point to the center represents the hour circle of the body. From the celestial equator, shown as a circle midway between the center and the outer edge, measure the declination (from the almanac) of the body toward the center if the pole and declination have the same name (both N or both S), and away from the center if they are of contrary name. Use the scale along the north-south azimuth line of any template as a declination scale. The meridian angle-declination template (the latitude 5° template of No. 2102C) has an open slot with declination graduations along one side, to assist in plotting positions, as shown in Figure 1539b. In the illustration, the celestial body being located has a 360° – SHA of 285°, and a declination of 14.5°S. It is not practical to attempt to plot to greater precision than the nearest 0.1°. Positions of Venus, Mars, Jupiter, and Saturn, on June 1, 1975, are shown plotted on the star base in Figure 1539c. It is sometimes desirable to plot positions of the sun and moon to assist in planning. Plotted positions of stars need not be changed. Plotted positions of bodies of the solar system should be replotted from time to time, the more rap-

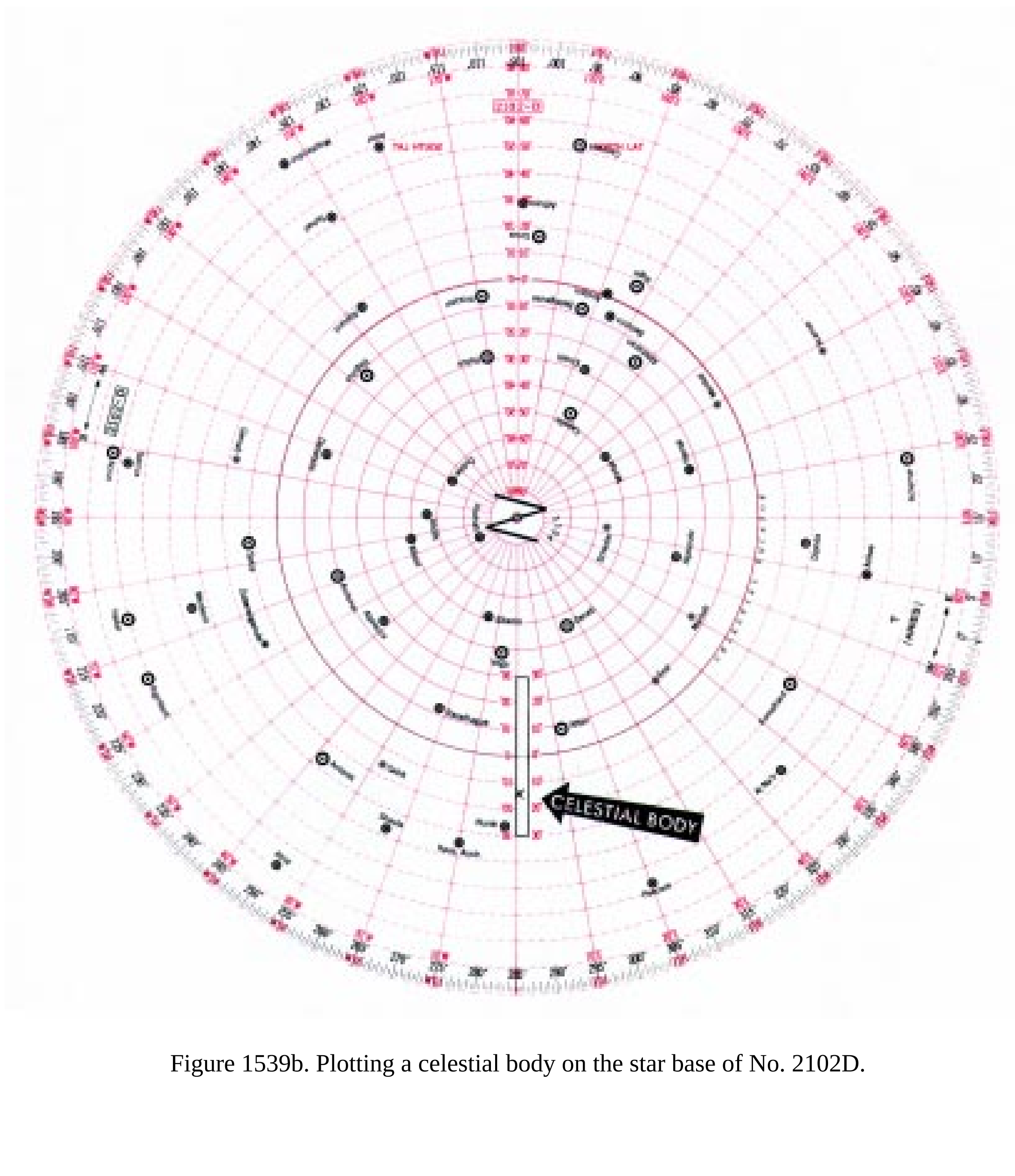


Figure 1539b. Plotting a celestial body on the star base of No. 2102D.

idly moving ones more often than others. The satisfactory interval for each body can be determined by experience. It is good practice to record the date of each plotted position of a body of the solar system, to serve later as an indication of the interval since it was plotted.

To orient the template properly for any given time, proceed as follows: enter the almanac with GMT, and determine GHA ♈ at this time. Apply the longitude to GHA ♈, subtracting if west, or adding if east, to determine LHA ♈. If LMT is substituted for GMT in entering the almanac, LHA ♈ can be taken directly from the almanac, to sufficient accuracy for orienting the star finder template. Select the template for the latitude nearest that of the observer, and center it over the star base, being careful that the correct sides (north or south to agree with the latitude) of both template and star base are used. Rotate the template relative to the star base, until the arrow on the celestial meridian (the north-south azimuth line) is over LHA ♈ on the star based graduations. The small cross at the origin of both families of curves now represents the zenith of the observer. The approximate altitude and azimuth of the celestial bodies above the horizon can be visually interpolated from the star finder. Consider Polaris (not shown) as at the north celestial pole. For more accurate results, the template can be lifted clear of the center peg of the star base, and shifted along the celestial meridian until the latitude, on the altitude scale, is over the pole. This refinement is not needed for normal use of the device. It should not be used for a latitude differing more than 5° from that for which the curves were drawn. If the altitude and azimuth of an identified body shown on the star base are known, the template can be oriented by rotating it until it is in correct position relative to that body.

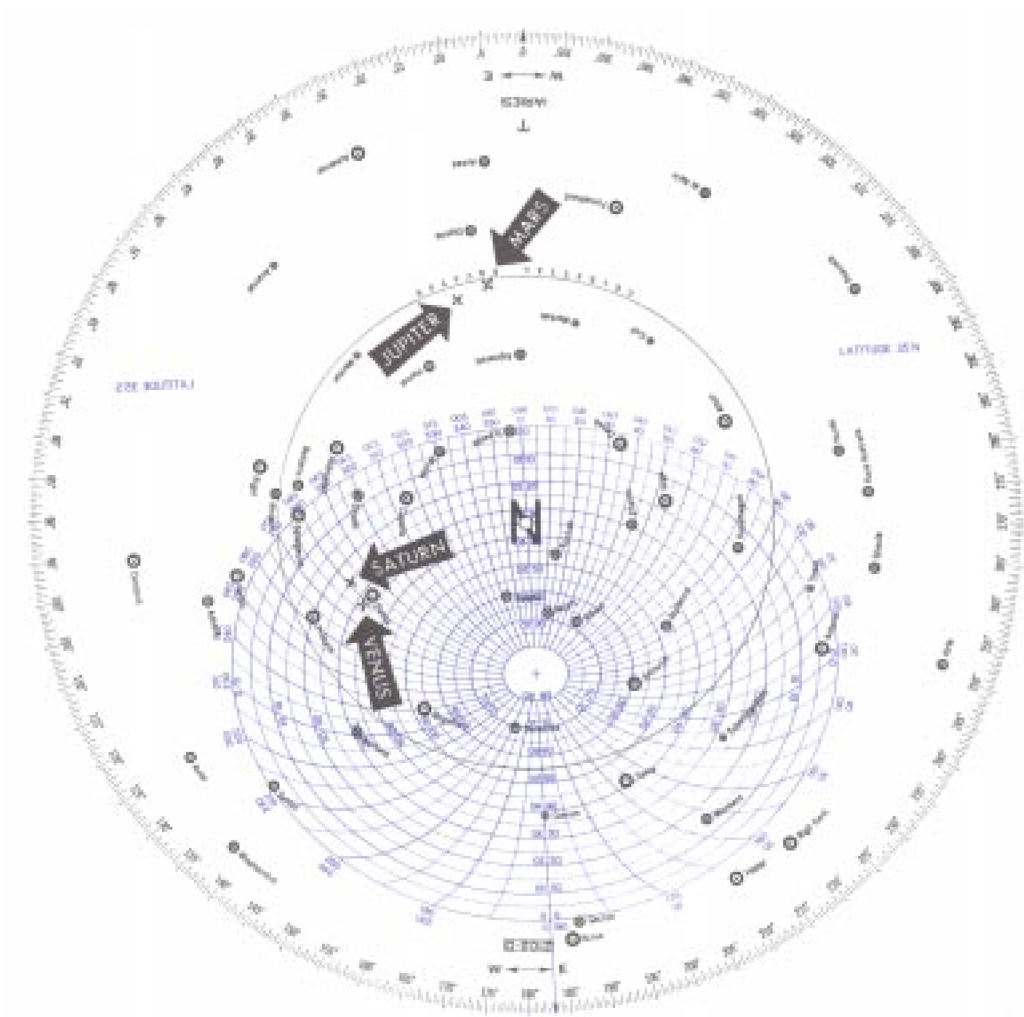


Figure 1539c. A template in place over the star base of No. 2102D.

1540. *Sight Reduction Tables for Air Navigation (Pub. No. 249)*

Volume I of *Pub. No. 249* can be used as a star finder for the stars tabulated at any given time. For these bodies the altitude and azimuth are tabulated for each 1° of latitude and 1° of LHA ♈ (2° beyond latitude 69°). The principal limitation is the small number of stars listed.

1541. Air Almanac Sky Diagram

Near the back of the Air Almanac are a number of sky diagrams. These are azimuthal equidistant projections of the celestial sphere on the plane of the horizon, at latitudes 75°N, 50°N, 25°N, 0°, 25°S, and 50°S, at intervals of 2 hours of local mean time each month. A number of the brighter stars, the visible planets, and several positions of the moon are shown at their correct altitude and azimuth. These are of limited value to marine navigators because of their small scale; the large increments of latitude, time, and date; and the limited number of bodies shown. However, in the absence of other methods, particularly a star finder, these diagrams can be useful. Allowance can be made for variations from the conditions for which each diagram is constructed. Instructions for use of the diagrams are included in the Air Almanac.

1542. Identification By Computation

If the altitude and azimuth of the celestial body, and the approximate latitude of the observer, are known, the navigational triangle can be solved for meridian angle and declination. The meridian angle can be converted to LHA, and this to GHA. With this and GHA ♈ at the time of observation, the SHA of the body can be determined. With SHA and declination, one can identify the body by reference to an almanac. Any method of solving a spherical triangle, with two sides and the included angle being given, is suitable for this purpose. A large-scale, carefully-drawn diagram on the plane of the celestial meridian, using the refinement shown in Figure 1529f, should yield satisfactory results.

Although no formal star identification tables are included in *Pub. No. 229*, a simple approach to star identification is to scan the pages of the appropriate latitudes, and observe the combination of arguments which give the altitude and azimuth angle of the observation. Thus the declination and LHA Z are determined directly. The star's SHA is found from SHA ★ = LHA ★ – LHA ♈. From these quantities the star can be identified from the Nautical Almanac.

Another solution is available through an interchange of arguments using the nearest integral values. The procedure consists of entering *Pub. No. 229* with the observer's latitude (same name as declination), with the observed azimuth angle (converted from observed true azimuth as required) as LHA and the observed altitude as declination, and extracting from the tables the altitude and azimuth angle respondents. The extracted altitude becomes the body's declination; the extracted azimuth angle (or its supplement) is the meridian angle of the body. Note that the tables are always entered with latitude of same name as declination. In north latitudes the tables can be entered with true azimuth as LHA.

If the respondents are extracted from above the C-S Line on a right-hand page, the name of the latitude is actually contrary to the declination. Otherwise, the declination of the body has the same name as the latitude. If the azimuth angle respondent is extracted from above the C-S Line, the supplement of the tabular value is the meridian angle, t, of the body. If the body is east of the observer's meridian, LHA = 360° – t; if the body is west of the meridian, LHA = t.

CHAPTER 16

INSTRUMENTS FOR CELESTIAL NAVIGATION

THE MARINE SEXTANT

1600. Description And Use

The marine sextant measures the angle between two points by bringing the direct ray from one point and a double-reflected ray from the other into coincidence. Its principal use is to measure the altitudes of celestial bodies above the visible sea horizon. It may also be used to measure vertical angles to find the range from an object of known height. Sometimes it is turned on its side and used for measuring the angular distance between two terrestrial objects.

A marine sextant can measure angles up to approximately 120°. Originally, the term "sextant" was applied to the navigator's double-reflecting, altitude-measuring instrument only if its arc was 60° in length, or 1/6 of a circle, permitting measurement of angles from 0° to 120°. In modern usage the term is applied to all modern navigational altitude-measuring instruments regardless of angular range or principles of operation.

1601. Optical Principles Of A Sextant

When a plane surface reflects a light ray, the angle of reflection equals the angle of incidence. The angle between the first and final directions of a ray of light that has undergone double reflection in the same plane is twice the angle the two reflecting surfaces make with each other (Figure 1601).

In Figure 1601, AB is a ray of light from a celestial body.

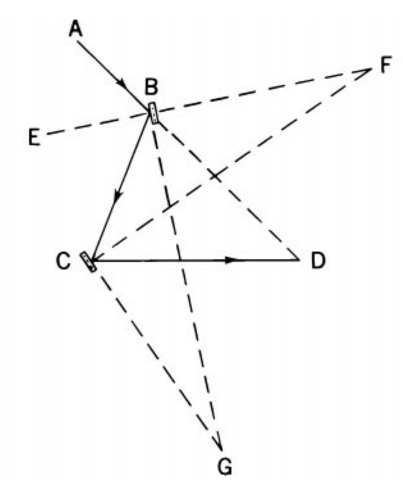


Figure 1601. Optical principle of the marine sextant.

The index mirror of the sextant is at B, the horizon glass at C, and the eye of the observer at D. Construction lines EF and CF are perpendicular to the index mirror and horizon glass, respectively. Lines BG and CG are parallel to these mirrors. Therefore, angles BFC and BGC are equal because their sides are mutually perpendicular. Angle BGC is the inclination of the two reflecting surfaces. The ray of light AB is reflected at mirror B, proceeds to mirror C, where it is again reflected, and then continues on to the eye of the observer at D. Since the angle of reflection is equal to the angle of incidence,

ABE = EBC, and ABC = 2EBC.
BCF = FCD, and BCD = 2BCF.

Since an exterior angle of a triangle equals the sum of the two non adjacent interior angles,

ABC = BDC+BCD, and EBC = BFC+BCF.
Transposing,
BDC = ABC-BCD, and BFC = EBC-BCF.

Substituting 2EBC for ABC, and 2BCF for BCD in the first of these equations,

BDC = 2EBC-2BCF, or BDC=2 (EBC-BCF).

Since BFC=EBC - BCF, and BFC = BGC, therefore

BDC = 2BFC = 2BGC.

That is, BDC, the angle between the first and last directions of the ray of light, is equal to 2BGC, twice the angle of inclination of the reflecting surfaces. Angle BDC is the altitude of the celestial body.

If the two mirrors are parallel, the incident ray from any observed body must be parallel to the observer's line of sight through the horizon glass. In that case, the body's altitude would be zero. The angle that these two reflecting surfaces make with each other is one-half the observed angle. The graduations on the arc reflect this half angle relationship between the angle observed and the mirrors' angle.

1602. Micrometer Drum Sextant

Figure 1602 shows a modern marine sextant, called a **micrometer drum sextant**. In most marine sextants, brass or aluminum comprise the **frame**, A. Frames come in various designs; most are similar to this. Teeth mark the outer

edge of the **limb**, B; each tooth marks one degree of altitude. The altitude graduations, C, along the limb, mark the **arc**. Some sextants have an arc marked in a strip of brass, silver, or platinum inlaid in the limb.

The **index arm**, D, is a movable bar of the same material as the frame. It pivots about the center of curvature of the limb. The **tangent screw**, E, is mounted perpendicularly on the end of the index arm, where it engages the teeth of the limb. Because the observer can move the index arm through the length of the arc by rotating the tangent screw, this is sometimes called an “endless tangent screw.” Contrast this with the limited-range device on older instruments. The **release**, F, is a spring-actuated clamp that keeps the tangent screw engaged with the limb’s teeth. The observer can disengage the tangent screw and move the index arm along the limb for rough adjustment. The end of the tangent screw mounts a **micrometer drum**, G, graduated in minutes of altitude. One complete turn of the drum moves the index arm one degree along the arc. Next to the micrometer drum and fixed on the index arm is a **vernier**, H, that reads in fractions of a minute. The vernier shown is graduated into ten parts, permitting readings to $^1/_{10}$ of a minute of arc (0.1'). Some sextants (generally of European manufacture) have verniers graduated into only five parts, permitting readings to 0.2'.

The **index mirror**, I, is a piece of silvered plate glass mounted on the index arm, perpendicular to the plane of the instrument, with the center of the reflecting surface directly over the pivot of the index arm. The **horizon glass**, J, is a piece of optical glass silvered on its half nearer the frame. It is mounted on the frame, perpendicular to the plane of the sextant. The index mirror and horizon glass are mounted so that their surfaces are parallel when the micrometer drum is set at 0°, if the instrument is in perfect adjustment. **Shade glasses**, K, of varying darkness are mounted on the sextant’s frame in front of the index mirror and horizon glass. They can be moved into the line of sight as needed to reduce the intensity of light reaching the eye.

The **telescope**, L, screws into an adjustable collar in line with the horizon glass and parallel to the plane of the instrument. Most modern sextants are provided with only one telescope. When only one telescope is provided, it is of the “erect image type,” either as shown or with a wider “object glass” (far end of telescope), which generally is shorter in length and gives a greater field of view. The second telescope, if provided, may be the “inverting type.” The inverting telescope, having one lens less than the erect type, absorbs less light, but at the expense of producing an inverted image. A small colored glass cap is sometimes provided, to be placed over the “eyepiece” (near end of telescope) to reduce glare. With this in place, shade glasses are generally not needed. A “peep sight,” or clear tube which serves to direct the line of sight of the observer when no telescope is used, may be fitted.

Sextants are designed to be held in the right hand. Some have a small light on the index arm to assist in reading altitudes. The batteries for this light are fitted inside a recess in the **handle**, M. Not clearly shown in Figure 1602 are the **tangent screw**, E, and the three legs.

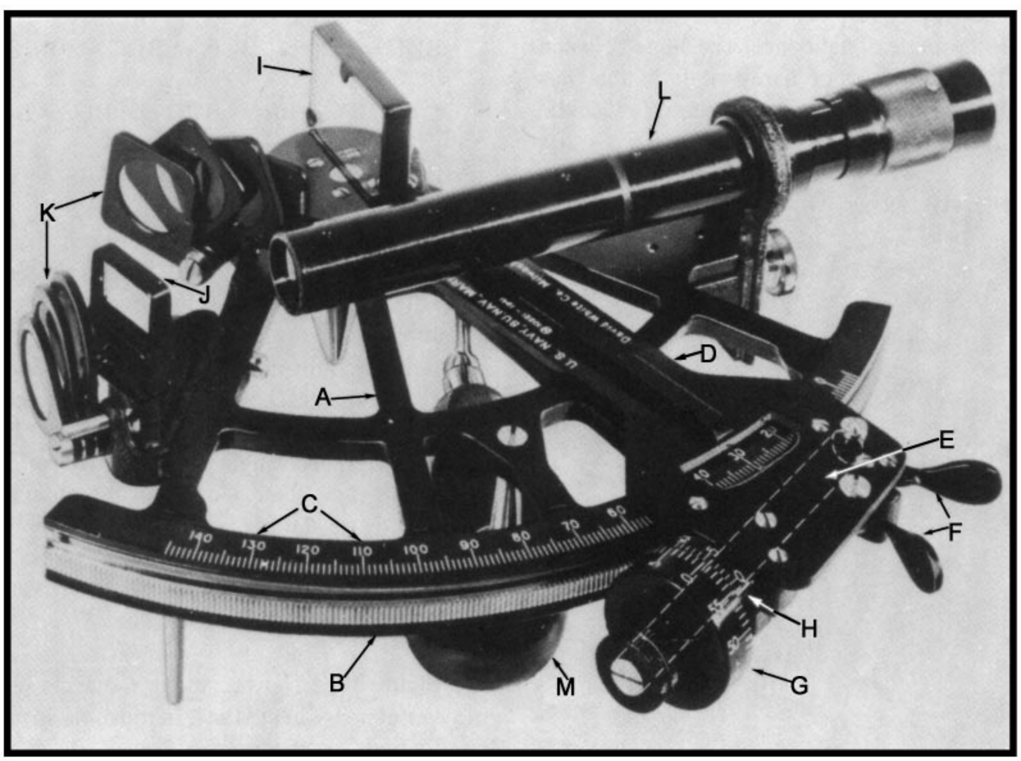


Figure 1602. U.S. Navy Mark 2 micrometer drum sextant.

There are two basic designs commonly used for mounting and adjusting mirrors on marine sextants. On the U.S. Navy Mark 3 and certain other sextants, the mirror is mounted so that it can be moved against retaining or mounting springs within its frame. Only one perpendicular adjustment screw is required. On the U.S. Navy Mark 2 and other sextants the mirror is fixed within its frame. Two perpendicular adjustment screws are required. One screw must be loosened before the other screw bearing on the same surface is tightened.

1603. Vernier Sextant

Most recent marine sextants are of the micrometer drum type, but at least two older-type sextants are still in use. These differ from the micrometer drum sextant principally in the manner in which the final reading is made. They are called **vernier sextants**.

The **clamp screw vernier sextant** is the older of the two. In place of the modern release clamp, a clamp screw is fitted on the underside of the index arm. To move the index arm, the clamp screw is loosened, releasing the arm. When the arm is placed at the approximate altitude of the body being observed, the clamp screw is tightened. Fixed to the clamp screw and engaged with the index arm is a long tangent screw. When this screw is turned, the index arm moves slowly, permitting accurate setting. Movement of the index arm by the tangent screw is limited to the length of the screw (several degrees of arc). Before an altitude is measured, this screw should be set to the approximate mid-point of its range. The final reading is made on a vernier set in the index arm below the arc. A small microscope or magnifying glass fitted to the index arm is used in making the final reading.

The **endless tangent screw vernier sextant** is identical to the micrometer drum sextant, except that it has no drum, and the fine reading is made by a vernier along the arc, as with th-eclamp screw vernier sextant. The release is the same as on the micrometer drum sextant, and teeth are cut into the underside of the limb which engage with the endless tangent screw.

1604. Sextant Sun Sights

Hold the sextant vertically and direct the sight line at the horizon directly below the sun. After moving suitable shade glasses into the line of sight, move the index arm outward along the arc until the reflected image appears in the horizon glass near the direct view of the horizon. Rock the sextant slightly to the right and left to ensure it is perpendicular. As the observer rocks the sextant, the image of the sun appears to move in an arc, and the observer may have to turn slightly to prevent the image from moving off the horizon glass.

The sextant is vertical when the sun appears at the bottom of the arc. This is the correct position for making the observation. The sun's reflected image appears at the center of the horizon glass; one half appears on the silvered part, and the other half appears on the clear part. Move the index arm with the drum or vernier slowly until the sun appears to be resting *exactly* on the horizon, tangent to the lower limb. The novice observer needs practice to determine the exact point of tangency. Beginners often err by bringing the image down too far.

Some navigators get their most accurate observations by letting the body contact the horizon by its own motion, bringing it slightly below the horizon if rising, and above if setting. At the instant the horizon is tangent to the disk, the navigator notes the time. The sextant altitude is the uncorrected reading of the sextant.

1605. Sextant Moon Sights

When observing the moon, follow the same procedure as for the sun. Because of the phases of the moon, the upper limb of the moon is observed more often than that of the sun. When the terminator (the line between light and dark areas) is nearly vertical, be careful in selecting the limb to shoot. Sights of the moon are best made during either daylight hours or that part of twilight in which the moon is least luminous. At night, false horizons may appear below the moon because the moon illuminates the water below it.

1606. Sextant Star And Planet Sights

Use one of these three methods when making the initial altitude approximation on a star or planet:

Method 1. Set the index arm and micrometer drum on 0° and direct the line of sight at the body to be observed. Then, while keeping the reflected image of the body in the mirrored half of the horizon glass, swing the index arm out and rotate the frame of the sextant down. Keep the reflected image of the body in the mirror until the horizon appears in the clear part of the horizon glass. Then, make the observation. When there is little contrast between brightness of the sky and the body, this procedure is difficult. If the body is "lost" while it is being brought down, it may not be recovered without starting over again.

Method 2. Direct the line of sight at the body while holding the sextant upside down. Slowly move the index-arm out until the horizon appears in the horizon glass. Then invert the sextant and take the sight in the usual manner.

Method 3. Determine in advance the approximate altitude and azimuth of the body by a star finder such as No. 2102D. Set the sextant at the indicated altitude and face in the direction of the azimuth. The image of the body should appear in the horizon glass with a little searching.

When measuring the altitude of a star or planet, bring its *center* down to the horizon. Stars and planets have no discernible upper or lower limb; observe the center of the point of light. Because stars and planets have no discernible limb and because their visibility may be limited, the method of letting a star or planet intersect the horizon by its own motion is not recommended. As with the sun and moon, however, "rock the sextant" to establish perpendicularity.

1607. Taking A Sight

Predict expected altitudes and azimuths for up to eight bodies when preparing to take celestial sights. Choose the stars and planets that give the best bearing spread. Try to select bodies with a predicted altitude between 30° and 70°. Take sights of the brightest stars first in the evening; take sights of the brightest stars last in the morning.

Occasionally, fog, haze, or other ships in a formation may obscure the horizon directly below a body which the navigator wishes to observe. If the arc of the sextant is sufficiently long, a **back sight** might be obtained, using the opposite point of the horizon as the reference. For this the observer faces away from the body and observes the supplement of the altitude. If the sun or moon is observed in this manner, what appears in the horizon glass to be the lower limb is in fact the upper limb, and vice versa. In the case of the sun, it is usually preferable to observe what appears to be the upper limb. The arc that appears when rocking the sextant for a back sight is inverted; that is, the highest point indicates the position of perpendicularity.

If more than one telescope is furnished with the sextant, the erecting telescope is used to observe the sun. A wider field of view is present if the telescope is not used. The collar into which the sextant telescope fits may be adjusted in or out, in relation to the frame. When moved in, more of the mirrored half of the horizon glass is visible to the navigator, and a star or planet is more easily observed when the sky is relatively bright. Near the darker limit of twilight, the telescope can be moved out, giving a broader view of the clear half of the glass, and making the less distinct horizon more easily discernible. If both eyes are kept open until the last moments of an observation, eye strain will be lessened. Practice will permit observations to be made quickly, reducing inaccuracy due to eye fatigue.

When measuring an altitude, have an assistant note and record the time if possible, with a "stand-by" warning when the measurement is almost ready, and a "mark" at the moment a sight is made. If a flashlight is needed to see the comparing watch, the assistant should be careful not to interfere with the navigator's night vision.

If an assistant is not available to time the observations, the observer holds the watch in the palm of his left hand, leaving his fingers free to manipulate the tangent screw of the sextant. After making the observation, he notes the time as quickly as possible. The delay between completing the altitude observation and noting the time should not be more than one or two seconds.

1608. Reading The Sextant

Reading a micrometer drum sextant is done in three steps. The degrees are read by noting the position of the arrow on the index arm in relation to the arc. The minutes are read by noting the position of the zero on the vernier with

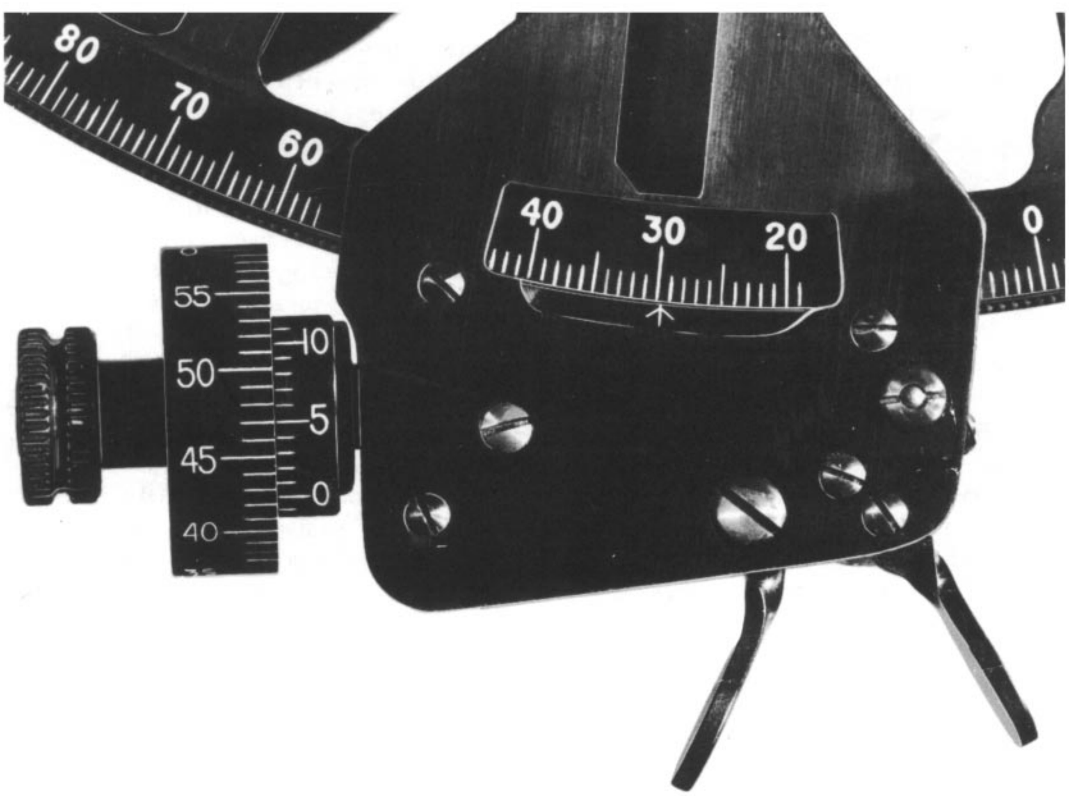


Figure 1608a. Micrometer drum sextant set at 29° 42.5'.

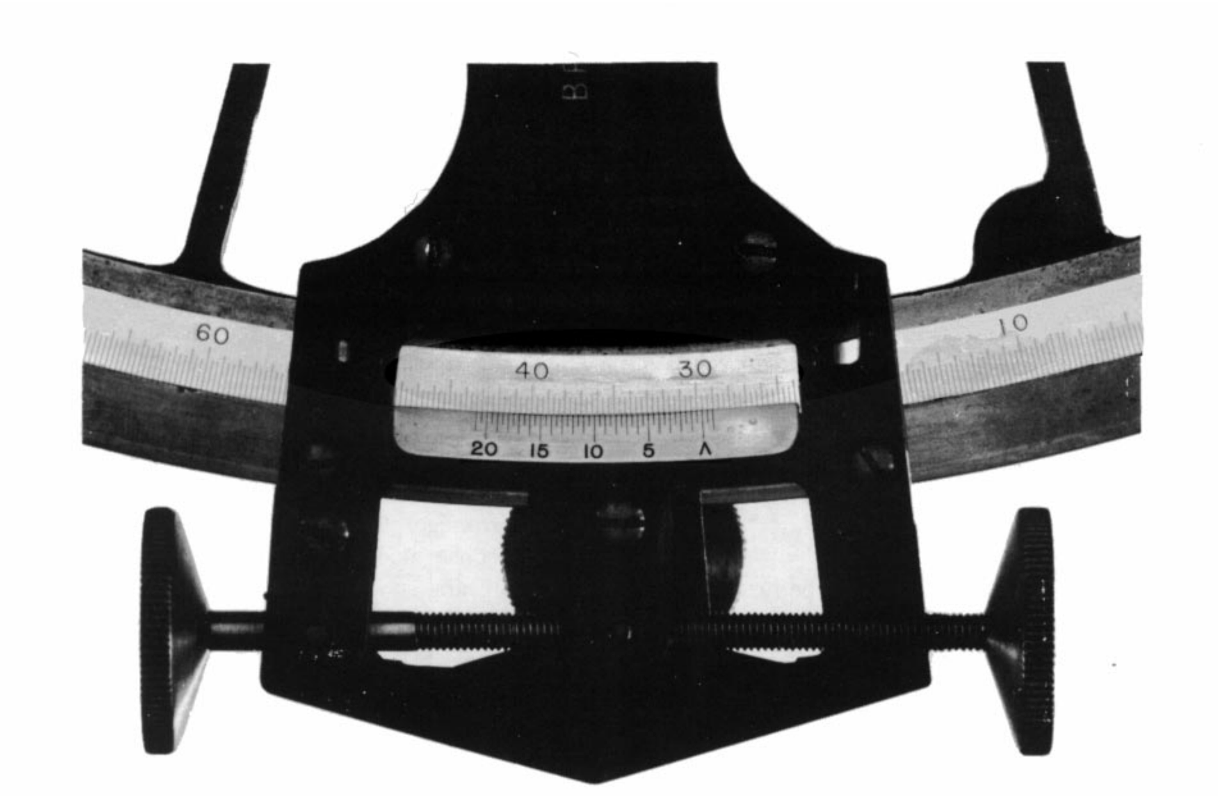


Figure 1608b. Vernier sextant set at 29°42'30".

relation to the graduations on the micrometer drum. The fraction of a minute is read by noting which mark on the vernier most nearly coincides with one of the graduations on the micrometer drum. This is similar to reading the time with the hour, minute, and second hands of a watch. In both, the relationship of one part of the reading to the others should be kept in mind. Thus, if the hour hand of a watch were about on "4," one would know that the time was about four o'clock. But if the minute hand were on "58," one would know that the time was 0358 (or 1558), not 0458 (or 1658). Similarly, if the arc indicated a reading of about 40°, and 58' on the micrometer drum were opposite zero on the vernier, one would know that the reading was 39° 58', not 40°58'. Similarly, any doubt as to the correct minute can be removed by noting the fraction of a minute from the position of the vernier. In Figure 1608a the reading is 29° 42.5'. The arrow on the index mark is between 29° and 30°, the zero on the vernier is between 42' and 43', and the 0.5' graduation on the vernier coincides with one of the graduations on the micrometer drum.

The principle of reading a vernier sextant is the same, but the reading is made in two steps. Figure 1608b shows a typical altitude setting. Each degree on the arc of this sextant is graduated into three parts, permitting an initial reading by the reference mark on the index arm to the nearest 20' of arc. In this illustration the reference mark lies between 29°40' and 30°00', indicating a reading between these values. The reading for the fraction of 20' is made using the vernier, which is engraved on the index arm and has the small reference mark as its zero graduation. On this vernier, 40 graduations coincide with 39 graduations on the arc. Each graduation on the vernier is equivalent to 1/40 of one graduation of 20' on the arc, or 0.5', or 30". In the illustration, the vernier graduation representing 2 1/2' (2'30") most nearly coincides with one of the graduations on the arc. Therefore, the reading is 29°42'30", or 29°42.5', as before. When a vernier of this type is used, any doubt as to which mark on the vernier coincides with a graduation on the arc can usually be resolved by noting the position of the vernier mark on each side of the one that seems to be in coincidence.

Negative readings, such as a negative index correction, are made in the same manner as positive readings; the various figures are added algebraically. Thus, if the three parts of a micrometer drum reading are (-)1°, 56' and 0.3', the total reading is (-)1° + 56' + 0.3' = (-)3.7'.

1609. Developing Observational Skill

A well-constructed marine sextant is capable of measuring angles with an instrument error not exceeding 0.1'. Lines of position from altitudes of this accuracy would not be in error by more than about 200 yards. However, there are various sources of error, other than instrumental, in altitudes measured by sextant. One of the principal sources is the observer.

The first fix a student celestial navigator plots is likely to be disappointing. Most navigators require a great amount of practice to develop the skill necessary for good observa-

tions. But practice alone is not sufficient. Good technique should be developed early and refined throughout the navigator's career. Many good pointers can be obtained from experienced navigators, but each develops his own technique, and a practice that proves successful for one observer may not help another. Also, an experienced navigator is not necessarily a good observer. Navigators have a natural tendency to judge the accuracy of their observations by the size of the figure formed when the lines of position are plotted. Although this is some indication, it is an imperfect one, because it does not indicate errors of individual observations, and may not reflect constant errors. Also, it is a compound of a number of errors, some of which are not subject to the navigator's control.

Lines of position from celestial observations can be compared with good positions obtained by electronics or piloting. Common sources of error are:

1. The sextant may not be rocked properly.
2. Tangency may not be judged accurately.
3. A false horizon may have been used.
4. Subnormal refraction (dip) might be present.
5. The height of eye may be wrong.
6. Time might be in error.
7. The index correction may have been determined incorrectly.
8. The sextant might be out of adjustment.
9. An error may have been made in the computation.

Generally, it is possible to correct observation technique errors, but occasionally a personal error will persist. This error might vary as a function of the body observed, degree of fatigue of the observer, and other factors. For this reason, a personal error should be applied with caution.

To obtain greater accuracy, take a number of closely-spaced observations. Plot the resulting altitudes versus time and fair a curve through the points. Unless the body is near the celestial meridian, this curve should be a straight line. Use this graph to determine the altitude of the body at any time covered by the graph. It is best to use a point near the middle of the line. Using a calculator to reduce the sight will also yield greater accuracy because of the rounding errors inherent in the use of sight reduction tables.

A simpler method involves making observations at equal intervals. This procedure is based upon the assumption that, unless the body is on the celestial meridian, the change in altitude should be equal for equal intervals of time. Observations can be made at equal intervals of altitude or time. If time intervals are constant, the mid time and the average altitude are used as the observation. If altitude increments are constant, the average time and mid altitude are used.

If only a small number of observations is available, reduce and plot the resulting lines of position; then adjust them to a common time. The average position of the line might be used, but it is generally better practice to use the middle line. Reject any observation considered unreliable when determining the average.

1610. Care Of The Sextant

A sextant is a rugged instrument. However, careless handling or neglect can cause it irreparable harm. If you drop it, take it to an instrument repair shop for testing and inspection. When not using the sextant, stow it in a sturdy and sufficiently padded case. Keep the sextant out of excessive heat and dampness. Do not expose it to excessive vibration. Do not leave it unattended when it is out of its case. Do not hold it by its limb, index arm, or telescope. Liftit by its frame or handle. Do not lift it by its arc or index bar.

Next to careless handling, moisture is the sextant's greatest enemy. Wipe the mirrors and the arc after each use. If the mirrors get dirty, clean them with lens paper and a small amount of alcohol. Clean the arc with ammonia; never use a polishing compound. When cleaning, do not apply excessive pressure to any part of the instrument.

Silica gel kept in the sextant case will help keep the instrument free from moisture and preserve the mirrors. Occasionally heat the silica gel to remove the absorbed moisture.

Rinse the sextant with fresh water if sea water gets on it. Wipe the sextant gently with a soft cotton cloth and dry the optics with lens paper.

Glass optics do not transmit all the light received because glass surfaces reflect a small portion of light incident on their face. This loss of light reduces the brightness of the object viewed. Viewing an object through several glass optics affects the perceived brightness and makes the image indistinct. The reflection also causes glare which obscures the object being viewed. To reduce this effect to a minimum, the glass optics are treated with a thin, fragile, anti-reflection coating. Therefore, apply only light pressure when polishing the coated optics. Blow loose dust off the lens before wiping them so grit does not scratch the lens.

Frequently oil and clean the tangent screw and the teeth on the side of the limb. Use the oil provided with the sextant or an all-purpose light machine oil. Occasionally set the index arm of an endless tangent screw at one extremity of the limb, oil it lightly, and then rotate the tangent screw over the length of the arc. This will clean the teeth and spread oil over them. When stowing a sextant for a long period, clean it thoroughly, polish and oil it, and protect its arc with a thin coat of petroleum jelly.

If the mirrors need re-silvering, take the sextant to an instrument shop.

1611. Non Adjustable Sextant Errors

The non-adjustable sextant errors are prismatic error, graduation error, and centering error.

Prismatic error occurs when the faces of the shade

glasses and mirrors are not parallel. Error due to lack of parallelism in the shade glasses may be called **shade error**. The navigator can determine shade error in the shade glasses near the index mirror by comparing an angle measured when a shade glass is in the line of sight with the same angle measured when the glass is not in the line of sight. In this manner, determine and record the error for each shade glass. Before using a combination of shade glasses, determine their combined error. If certain observations require additional shading, use the colored telescope eyepiece cover. This does not introduce an error because direct and reflected rays are traveling together when they reach the cover and are, therefore, affected equally by any lack of parallelism of its two sides.

Graduation errors occur in the arc, micrometer drum, and vernier of a sextant which is improperly cut or incorrectly calibrated. Normally, the navigator cannot determine whether the arc of a sextant is improperly cut, but the principle of the vernier makes it possible to determine the existence of graduation errors in the micrometer drum or vernier. This is a useful guide in detecting a poorly made instrument. The first and last markings on any vernier should align perfectly with one less graduation on the adjacent micrometer drum.

Centering error results if the index arm does not pivot at the exact center of the arc's curvature. Calculate centering error by measuring known angles after removing all adjustable errors. Use horizontal angles accurately measured with a theodolite as references for this procedure. Several readings by both theodolite and sextant should minimize errors. If a theodolite is not available, use calculated angles between the lines of sight to stars as the reference, comparing these calculated values with the values determined by the sextant. To minimize refraction errors, select stars at about the same altitude and avoid stars near the horizon. The same shade glasses, if any, used for determining index error should be used for measuring centering error.

The manufacturer normally determines the magnitude of all three non-adjustable errors and reports them to the user as **instrument error**. The navigator should apply the correction for this error to each sextant reading.

1612. Adjustable Sextant Error

The navigator should measure and remove the following adjustable sextant errors in the order listed:

1. **Perpendicularity Error:** Adjust first for perpendicularity of the index mirror to the frame of the sextant. To test for perpendicularity, place the index arm at about 35° on the arc and hold the sextant on its side with the index mirror up and toward the eye. Observe the direct and reflected views of the sextant arc, as illustrated in Figure 1612a. If the two views are not joined in a straight line, the index mirror is not perpendicular. If the reflected image is above the direct view, the mirror is inclined forward. If the reflected image is below the direct view, the mirror is inclined backward. Make the adjustment using two screws behind the index mirror.

2. **Side Error:** An error resulting from the horizon glass not being perpendicular is called **side error**. To test for side error, set the index arm at zero and direct the line of sight at a star. Then rotate the tangent screw back and forth so that the reflected image passes alternately above and below the direct view. If, in changing from one position to the other, the reflected image passes directly over the unreflected image, no side error exists. If it passes to one side, side error exists. Figure 1612b illustrates observations without side error (left) and with side error (right). Whether the sextant reads zero when the true and reflected images are in coincidence is immaterial for this test. An alternative method is to observe a vertical line, such as one edge of the mast of another vessel (or the sextant can be held on its side and the horizon used). If the direct and reflected portions do not form a continuous line, the horizon glass is not perpendicular to the

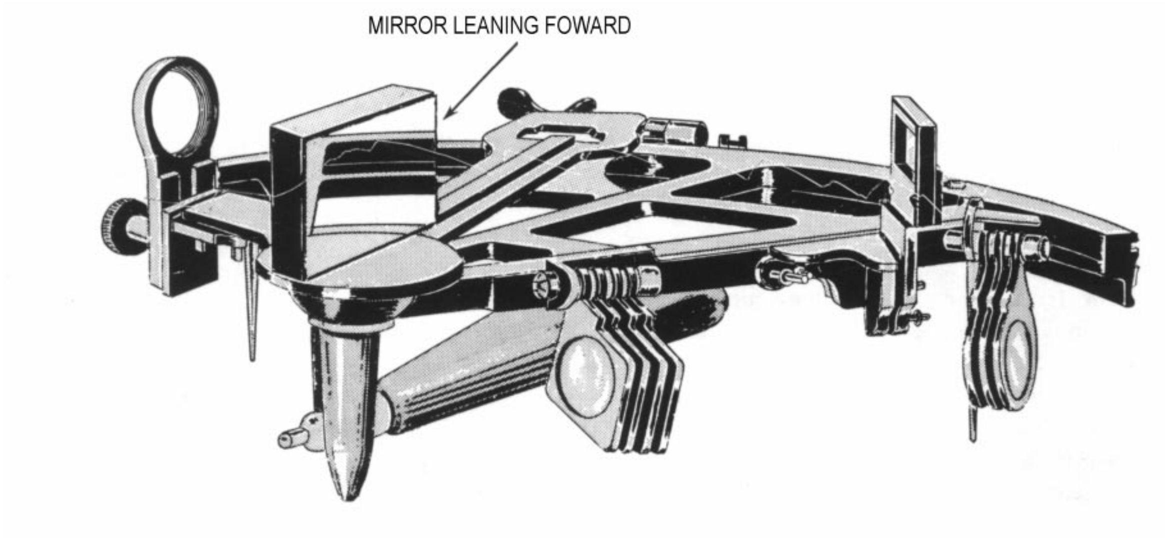


Figure 1612a. Testing the perpendicularity of the index mirror. Here the mirror is not perpendicular.

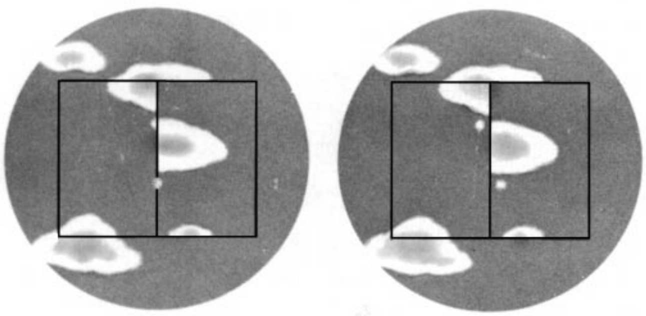


Figure 1612b. Testing the perpendicularity of the horizon glass. On the left, side error does not exist. At the right, side error does exist.

frame of the sextant. A third method involves holding the sextant vertically, as in observing the altitude of a celestial body. Bring the reflected image of the horizon into coincidence with the direct view until it appears as a continuous line across the horizon glass. Then tilt the sextant right or left. If the horizon still appears continuous, the horizon glass is perpendicular to the frame, but if the reflected portion appears above or below the part seen directly, the glass is not perpendicular. Make the appropriate adjustment using two screws behind the horizon glass.

3. **Collimation Error:** If the line of sight through the telescope is not parallel to the plane of the instrument, a **collimation error** will result. Altitudes measured will be greater than their actual values. To check for parallelism of the telescope, insert it in its collar and observe two stars 90° or more apart. Bring the reflected image of one into coincidence with the direct view of the other near either the right or left edge of the field of view (the upper or lower edge if the sextant is horizontal). Then tilt the sextant so that the stars appear near the opposite edge. If they remain in coincidence, the telescope is parallel to the frame; if they separate, it is not. An alternative method involves placing the telescope in its collar and then laying the sextant on a flat table. Sight along the frame of the sextant and have an assistant place a mark on the opposite bulkhead, in line with the frame. Place another mark above the first, at a distance equal to the distance from the center of the telescope to the frame. This second line should be in the center of the field of view of the telescope if the telescope is parallel to the frame. Adjust the collar to correct for non-parallelism.

4. **Index Error:** Index error is the error remaining after the navigator has removed perpendicularity error, side error, and collimation error. The index mirror and horizon glass not being parallel when the index arm is set exactly at zero is the major cause of index error. To test for parallelism of the mirrors, set the instrument at zero and direct the line of sight at the horizon. Adjust the sextant reading as necessary to cause both images of the horizon to come into line. The sextant's reading when the horizon comes into line is the index error. If the index error is positive, subtract it from each sextant reading. If the index error is negative, add it to each sextant reading.

1613. Selecting A Sextant

Carefully match the selected sextant to its required uses. For occasional small craft or student use, a plastic sextant may be adequate. A plastic sextant may also be appropriate for an emergency navigation kit. Accurate offshore navigation requires a quality metal instrument. For ordinary use in measuring altitudes of celestial bodies, an arc of 90° or slightly more is sufficient. If using a sextant for back sights or determining horizontal angles, purchase one with a longer arc. If necessary, have an experienced mariner examine the sextant and test it for non adjustable errors before purchase.

1614. The Artificial Horizon

Measurement of altitude requires an exact horizontal reference. At sea, the visible sea horizon normally provides this reference. If the horizon is not clearly visible, however, a different horizontal reference is required. Such a reference is commonly termed an **artificial horizon**. If it is attached to, or part of, the sextant, altitudes can be measured at sea, on land, or in the air, whenever celestial bodies are available for observations. Any horizontal reflecting surface will work. A pan of any liquid sheltered from the wind will serve. Foreign material on the surface of the liquid is likely to distort the image and introduce an error in the reading.

To use an external artificial horizon, stand or sit in such a position that the celestial body to be observed is reflected in the liquid, and is also visible in direct view. With the sextant, bring the double-reflected image into coincidence with the image appearing in the liquid. For a lower limb observation of the sun or the moon, bring the bottom of the double-reflected image into coincidence with the top of the image in the liquid. For an upper-limb observation, bring the opposite sides into coincidence. If one image covers the other, the observation is of the center of the body.

After the observation, apply the index correction and any other instrumental correction. Then take *half* the remaining angle and apply all other corrections except dip (height of eye) correction, since this is not applicable. If the center of the sun or moon is observed, omit the correction for semidiameter.

1615. Artificial Horizon Sextants

Various types of artificial horizons have been used, including a bubble, gyroscope, and pendulum. Of these, the bubble has been most widely used. This type of instrument is fitted as a backup system to inertial and other positioning systems in a few aircraft, fulfilling the requirement for a self-contained, non-emitting system. On land, a skilled observer using a 2-minute averaging bubble or pendulum sextant can measure altitudes to an accuracy of perhaps 2', (2 miles). This, of course, refers to the accuracy of measurement only,

and does not include additional errors such as abnormal refraction, deflection of the vertical, computing and plotting errors, etc. In steady flight through smooth air the error of a 2-minute observation is increased to perhaps 5 to 10 miles.

At sea, with virtually no roll or pitch, results should approach those on land. However, even a gentle roll causes large errors. Under these conditions observational errors of 10-16 miles are not unreasonable. With a moderate sea, errors of 30 miles or more are common. In a heavy sea, any useful observations are virtually impossible to obtain. Single altitude observations in a moderate sea can be in error by a matter of degrees.

When the horizon is obscured by ice or haze, polar navigators can sometimes obtain better results with an artificial-horizon sextant than with a marine sextant. Some artificial-horizon sextants have provision for making observations with the natural horizon as a reference, but results are not generally as satisfactory as by marine sextant. Because of their more complicated optical systems, and the need for providing a horizontal reference, artificial-horizon sextants are generally much more costly to manufacture than marine sextants.

Altitudes observed by artificial-horizon sextants are subject to the same errors as those observed by marine sextant, except that the dip (height of eye) correction does not apply. Also, when the center of the sun or moon is observed, no correction for semidiameter is required.

CHRONOMETERS

1616. The Marine Chronometer

The spring-driven **marine chronometer** is a precision timepiece. It is used aboard ship to provide accurate time for timing celestial observations. A chronometer differs from a spring-driven watch principally in that it contains a variable lever device to maintain even pressure on the mainspring, and a special balance designed to compensate for temperature variations.

A spring-driven chronometer is set approximately to Greenwich mean time (GMT) and is not reset until the instrument is overhauled and cleaned, usually at three-year intervals. The difference between GMT and chronometer time (C) is carefully determined and applied as a correction to all chronometer readings. This difference, called chronometer error (CE), is **fast** (F) if chronometer time is later than GMT, and **slow** (S) if earlier. The amount by which chronometer error changes in 1 day is called **chronometer rate**. An erratic rate indicates a defective instrument requiring repair.

The principal maintenance requirement is regular winding at about the same time each day. At maximum intervals of about three years, a spring-driven chronometer should be sent to a chronometer repair shop for cleaning and overhaul.

1617. Quartz Crystal Marine Chronometers

Quartz crystal marine chronometers have replaced spring-driven chronometers aboard many ships because of their greater accuracy. They are maintained on GMT directly from radio time signals. This eliminates chronometer error (CE) and watch error (WE) corrections. Should the second hand be in error by a readable amount, it can be reset electrically.

The basic element for time generation is a quartz crystal oscillator. The quartz crystal is temperature compensated and is hermetically sealed in an evacuated envelope. A calibrated adjustment capability is provided to adjust for the aging of the crystal.

The chronometer is designed to operate for a minimum of 1 year on a single set of batteries. A good marine chronometer has a built-in push button battery test meter. The meter face is marked to indicate when the battery should be replaced. The chronometer continues to operate and keep the correct time for at least 5 minutes while the batteries are changed. The chronometer is designed to accommodate the gradual voltage drop during the life of the batteries while maintaining accuracy requirements.

1618. Watches

A chronometer should not be removed from its case to time sights. Observations may be timed and ship's clocks set with a **comparing watch**, which is set to chronometer time (GMT) and taken to the bridge wing for recording sight times. In practice, a wrist watch coordinated to the nearest second with the chronometer will be adequate.

A stop watch, either spring wound or digital, may also be used for celestial observations. In this case, the watch is started at a known GMT by chronometer, and the elapsed time of each sight added to this to obtain GMT of the sight.

CHAPTER 17

AZIMUTHS AND AMPLITUDES

INTRODUCTION

1700. Compass Checks

At sea, the mariner is constantly concerned about the accuracy of the gyro compass. There are several ways to check the accuracy of the gyro. He can, for example, compare it with an accurate electronic navigator such as an inertial navigaton system. Lacking a sophisticated electronic navigation suite, he can use the celestial techniques of comparing the measured and calculated azimuths and amplitudes of celestial bodies. The difference between the calculated value and the value determined by gyro measurement is gyro error. This chapter discusses these procedures.

Theoretically, these procedures work with any celestial body. However, the sun and Polaris are used most often when measuring azimuths, and the sun when measuring amplitudes.

AZIMUTHS

1701. Compass Error By Azimuth Of The Sun

Mariners use *Pub 229, Sight Reduction Tables for Marine Navigation* to compute the sun's azimuth. They compare the computed azimuth to the azimuth measured with the compass to determine compass error. In computing an azimuth, interpolate the tabular azimuth angle for the difference between the table arguments and the actual values of declination, latitude, and local hour angle. Do this triple interpolation of the azimuth angle as follows:

1. Enter the *Sight Reduction Tables* with the nearest integral values of declination, latitude, and local hour angle. For each of these arguments, extract a base azimuth angle.
2. Reenter the tables with the same latitude and LHA arguments but with the declination argument 1° greater or less than the base declination argument, depending upon whether the actual declination is greater or less than the base argument. Record the difference between the respondent azimuth angle and the base azimuth angle and label it as the azimuth angle difference (Z Diff.).
3. Reenter the tables with the base declination and LHA arguments, but with the latitude argument 1° greater or less than the base latitude argument, depending upon whether the actual (usually DR) latitude is greater or less than the base argument. Record the Z Diff. for the increment of latitude.
4. Reenter the tables with the base declination and latitude arguments, but with the LHA argument 1° greater or less than the base LHA argument, depending upon whether the actual LHA is greater or less than the base argument. Record the Z Diff. for the increment of LHA.
5. Correct the base azimuth angle for each increment.

Example:

In DR latitude 33° 24.0'N, the azimuth of the sun is 096.5° pgc. At the time of the observation, the declination of the sun is 20° 13.8'N; the local hour angle of the sun is 316° 41.2'. Determine compass error.

Solution:

See Figure 1701 Enter the actual value of declination, DR latitude, and LHA. Round each argument to the nearest whole degree. In this case, round the declination and the latitude down to the nearest whole degree. Round the LHA up to the nearest whole degree. Enter the Sight Reduction Tables with these whole degree arguments and extract the base azimuth value for these rounded off arguments. Record the base azimuth value in the table.

As the first step in the triple interpolation process, increase the value of declination by 1° to 21° because the actual declination value was greater than the base declination. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 21°; (2) DR Latitude = 33°; (3) LHA = 317°. Record the tabulated azimuth for these arguments.

As the second step in the triple interpolation process, increase the value of latitude by 1° to 34° because the actual DR latitude was greater than the base latitude. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 20°; (2) DR Latitude = 34°; (3) LHA = 317°.

	Actual	Base Arguments	Base Z	Tab* Z	Z Diff.	Increments	Correction (Z Diff x Inc.÷ 60)
Dec.	20°13.8' N	20°	97.8°	96.4°	–1.4°	13.8'	–0.3°
DR Lar.	33°24.0' N	33°(Same)	97.8°	98.9°	+1.1°	24.0'	+0.4°
LHA	316°41.2'	317°	97.8°	97.1°	– 0.7°	18.8'	–0.2°

Base Z	97.8°
Corr.	(–) 0.1°
Z	N 97.7° E
Zn	097.7°
Zn pgc	096.5°
Gyro Error	1.2° E

Total Corr.	–0.1°

*Respondent for the two base arguments and 1° change from third base argument, in vertical order of Dec., DR Lat., and LHA.

Figure 1701. Azimuth by *Pub. No. 229*.

Record the tabulated azimuth for these arguments.

As the third and final step in the triple interpolation process, decrease the value of LHA to 316° because the actual LHA value was smaller than the base LHA. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 20°; (2) DR Latitude = 33°; (3) LHA = 316°. Record the tabulated azimuth for these arguments.

Calculate the Z Difference by subtracting the base azimuth from the tabulated azimuth. Be careful to carry the correct sign.

Z Difference = Tab Z - Base Z

Next, determine the increment for each argument by taking the difference between the actual values of each argument and the base argument. Calculate the correction for each of the three argument interpolations by multiplying the increment by the Z difference and dividing the resulting product by 60.

The sign of each correction is the same as the sign of the corresponding Z difference used to calculate it. In the above example, the total correction sums to -0.1'. Apply this value to the base azimuth of 97.8° to obtain the true azimuth 97.7°. Compare this to the compass reading of 096.5° pgc. The compass error is 1.2°E.

AZIMUTH OF POLARIS

1702. Compass Error By Azimuth Of Polaris

The Polaris tables in the *Nautical Almanac* list the azimuth of Polaris for latitudes between the equator and 65° N. Figure 2011 in Chapter 20 shows this table. Compare a compass bearing of Polaris to the tabular value of Polaris to determine compass error. The entering arguments for the table are LHA of Aries and observer latitude.

Example:

On March 17, 1994, at L 33° 15.0' N and 045° 00.0'W, at 02-00-00 GMT, Polaris bears 358.6°T by compass. Calculate the compass error.

Date	*17 March 1994*
Time (GMT)	*02-00-00*
GHA Aries	*204° 25.4'*
Longitude	*045° 00.0'W*
LHA Aries	*161° 25.4'*

Solution:

Enter the azimuth section of the Polaris table with the calculated LHA of Aries. In this case, go to the column for LHA Aries between 160° and 169°. Follow that column down and extract the value for the given latitude. Since the increment between tabulated values is so small, visual interpolation is sufficient. In this case, the azimuth for Polaris for the given LHA of Aries and the given latitude is 359.3°.

Tabulated Azimuth	*359.3°T*
Compass Bearing	*358.6°T*
Error	*0.7°E*

AMPLITUDES

1703. Amplitudes

A celestial body's **amplitude** is the arc between the observed body on the horizon and the point where the observer's horizon intersects the celestial equator. See Figure 1703.

Calculate an amplitude after observing a body on either the celestial or visual horizon. Compare a body's measured

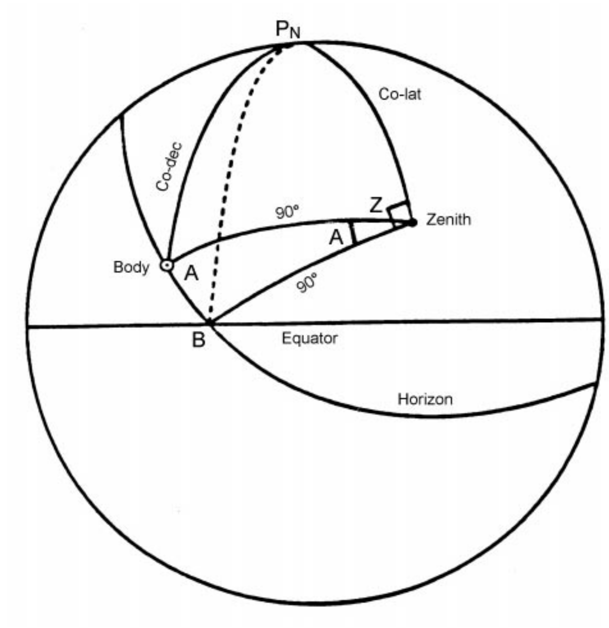


Figure 1703. The amplitude is the arc (A) between the observed body on the horizon and the point where the observer's horizon intersects the celestial equator.

amplitude with an amplitude extracted from the Amplitude table. The difference between the two values represents compass error.

Give amplitudes the suffix N if the body from which it was determined has a northern declination and S if it has a southern declination. Give the amplitudes the prefix E if the body is rising and W if the body is setting.

The values in the *Amplitude* table assume that the body is on the *celestial* horizon. The sun is on the celestial horizon when its lower limb is about two-thirds of a diameter above the visible horizon. The moon is on the celestial horizon when its upper limb is on the visible horizon. Planets and stars are on the celestial horizon when they are approximately one sun diameter above the visible horizon.

When using a body on the visible, not celestial, horizon, correct the observed amplitude from Table 23 Apply this table's correction to the *observed* amplitude and *not* to the amplitude extracted from the *Amplitude* table. For the sun, a planet, or a star, apply this correction to the observed amplitude in the direction *away from* the elevated pole. If using the moon, apply one-half of the Table 23 correction in the direction *towards* the elevated pole.

Navigators most often use the sun when determining amplitudes. The rule for applying the Table 23 corrections to a sun's observed amplitude is summarized as follows. If the DR latitude is north and the sun is rising, or if the DR latitude is south and the sun is setting, add the Table 23 correction to the observed amplitude. Conversely, if the DR latitude is north and the sun is setting, or the DR latitude is south and the sun is rising, then subtract the Table 23 correction from the observed amplitude.

The following two sections demonstrate the procedure for obtaining the amplitude of the sun on both the celestial and visible horizons.

1704. Amplitude Of The Sun On The Celestial Horizon

Example:

The DR latitude of a ship is 51° 24.6' N. The navigator observes the setting sun on the celestial horizon. Its declination is N 19° 40.4'. Its observed amplitude is W 32.9° N. (32.9° "north of west," or 302.9°).

Required:

Compass error.

Solution:

Interpolate in Table 22 for the sun's calculated amplitude as follows. See Figure 1704. The actual values for latitude and declination are L = 51.4° N and dec. = N 19.67°. Find the tabulated values of latitude and declination closest to these actual values. In this case, these tabulated values are L = 51° and dec. = 19.5°. Record the amplitude corresponding to these base values, 32.0°, as the base amplitude.

Next, holding the base declination value constant at 19.5°, increase the value of latitude to the next tabulated value: N 52°. Note that this value of latitude was increased because the actual latitude value was greater than the base value of latitude. Record the tabulated amplitude for L = 52° and dec. = 19.5°: 32.8°. Then, holding the base latitude value constant at 51°, increase the declination value to the next tabulated value: 20°. Record the tabulated amplitude for L = 51° and dec. = 20°: 32.9°.

The latitude's actual value (51.4°) is 0.4 of the way between the base value (51°) and the value used to determine the tabulated amplitude (52°). The declination's actual value (19.67°) is 0.3 of the way between the base value (19.5°) and the value used to determine the tabulated amplitude (20.0°). To determine the total correction to base amplitude, multiply these increments (0.4 and 0.3) by the respective difference between the base and tabulated values (+0.8 and +0.9, respectively) and sum the products. The total correction is +0.6°. Add the total correction (+0.6°) to the base amplitude (32.0°) to determine the final amplitude (32.6°).

Calculate the gyro error as follows:

Amplitude (observed) pgc	=	*W 32.9° N*
Amplitude (from Table 22)	=	*W 32.6° N*
Compass Error		*0.3°W*

1705. Amplitude Of The Sun On The Visible Horizon

Example:

The same problem as section 1704, except that the sun is setting on the visible horizon.

Required:
Compass error.

Solution:
Interpolate in Table 23 to determine the correction for the sun on the visible horizon as follows. See Figure 1705.. Choose as base values of latitude and declination the tabular values of latitude and declination closest to the actual values. In this case, these tabulated values are L = 51° N and dec. = 20°. Record the correction corresponding to these base values, 1.1°, as the base correction.

Completing the interpolation procedure indicates that the base correction (1.1°) is the actual correction.

Apply this correction in accordance with the rules discussed in section 1703. Since the vessel's latitude was north and the sun was setting, subtract the correction from the observed amplitude. The observed amplitude was W 32.9 N. Subtracting the 1.1° correction yields a corrected observed amplitude of W 31.8° N. From section 1704, the tabular amplitude was W 32.6° N.

Calculate the gyro error as follows:

Amplitude (from Table 22)	=	*W 32.6° N*
Amplitude (observed)	=	*W 31.8° N*
Compass Error		*0.8° E*

1706. Amplitude By Calculation

As an alternative to using Table 22 and Table 23, use the following formulas to calculate amplitudes:

a) Body on the celestial horizon:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin d}{\cos L}\right]$$

where d = celestial body's declination and L = observer's latitude.

b) Body on the visible horizon:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin d - \sin L \sin h}{\cos L \cos h}\right]$$

where d = celestial body's declination, L = observer's latitude, and h = – 0.7°.

Using the same example as in section 1704, d = 19.67° N and L = N 51.4°. If the sun is on the celestial horizon, its amplitude is:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin 19.67°}{\cos 51.4°}\right] = \text{W } 32.6° \text{ N.}$$

If the sun is on the visible horizon, its amplitude is:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin 19.67° - \sin 51.4° \sin -0.7°}{\cos 51.4° \cos -0.7°}\right]$$

$$= \text{W } 33.7° \text{ N}$$

Actual	Base	Base Amp.	Tab. Amp.	Diff.	Inc.	Correction
L=51.4°N	51°	32.0°	32.8°	+0.8°	0.4	+0.3°
dec=19.67°N	19.5°	32.0°	32.9°	+0.9°	0.3	+0.3°
					Total	+0.6°

Figure 1704. Interpolation in Table 22 for Amplitude.

Actual	Base	Base Corr.	Tab. Corr.	Diff.	Inc.	Correction
L=51.4°N	51°	1.1°	1.1°	0.0°	0.4	0.0°
dec=19.67°N	20°	1.1°	1.0°	-0.1°	0.2	0.0°

Figure 1705. Interpolation in Table 23 for Amplitude Correction.

CHAPTER 18

TIME

TIME IN NAVIGATION

1800. Solar Time

The earth's rotation on its axis causes the sun and other celestial bodies to appear to move across the sky from east to west each day. If a person located on the earth's equator measured the time interval between two successive transits overhead of a very distant star, he would be measuring the period of the earth's rotation. If he then made a similar measurement of the sun, the resulting time would be about 4 minutes longer. This is due to the earth's motion around the sun, which continuously changes the apparent place of the sun among the stars. Thus, during the course of a day the sun appears to move a little to the east among the stars so that the earth must rotate on its axis through more than 360° in order to bring the sun overhead again.

See Figure 1800. If the sun is on the observer's meridian when the earth is at point A in its orbit around the sun, it will not be on the observer's meridian after the earth has rotated through 360° because the earth will have moved along its orbit to point B. Before the sun is again on the observer's meridian, the earth must turn still more on its axis. The sun will be on the observer's meridian again when the earth has moved to point C in its orbit. Thus, during the course of a day the sun appears to move eastward with respect to the stars.

The apparent positions of the stars are commonly reckoned with reference to an imaginary point called the **vernal equinox**, the intersection of the celestial equator and the ecliptic. The period of the earth's rotation measured with respect to the vernal equinox is called a **sidereal day**. The period with respect to the sun is called an **apparent solar day**.

When measuring time by the earth's rotation, using the actual position of the sun results in **apparent solar time**.

Use of the apparent sun as a time reference results in time of non-constant rate for at least three reasons. First, revolution of the earth in its orbit is not constant. Second, time is measured along the celestial equator and the path of the real sun is not along the celestial equator. Rather, its path is along the ecliptic, which is tilted at an angle of 23° 27' with respect to the celestial equator. Third, rotation of the earth on its axis is not constant.

To obtain a constant rate of time, the apparent sun is replaced by a fictitious **mean sun**. This mean sun moves eastward along the celestial equator at a uniform speed equal

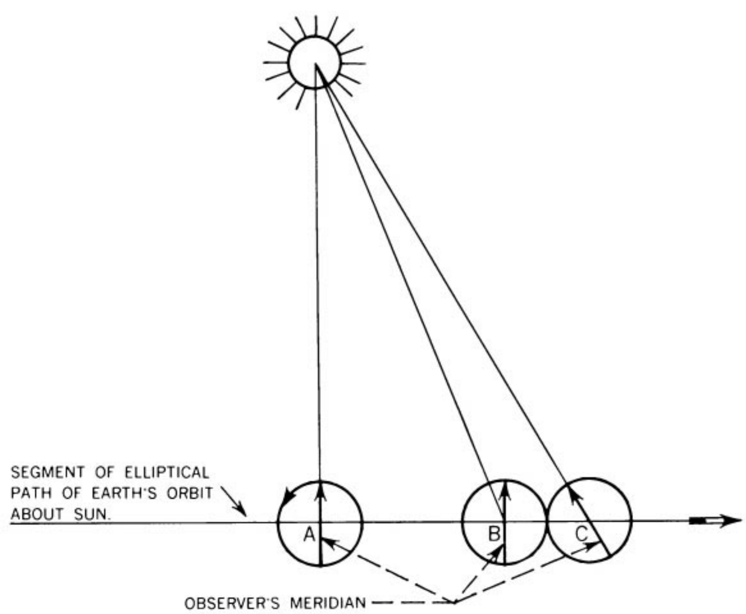


Figure 1800. Apparent eastward movement of the sun with respect to the stars.

to the average speed of the apparent sun along the ecliptic. This mean sun, therefore, provides a uniform measure of time which approximates the average apparent time. The speed of the mean sun along the celestial equator is 15° per hour of mean solar time.

1801. Equation Of Time

Mean solar time, or **mean time** as it is commonly called, is sometimes ahead of and sometimes behind apparent solar time. This difference, which never exceeds about 16.4 minutes, is called the **equation of time**.

The navigator most often deals with the equation of time when determining the time of **upper meridian passage** of the sun. The sun transits the observer's upper meridian at **local apparent noon**. Were it not for the difference in rate between the mean and apparent sun, the sun would be on the observer's meridian when the mean sun indicated 1200 local time. The apparent solar time of upper meridian passage, however, is offset from exactly 1200 mean solar time. This time difference, the equation of time at meridian transit, is listed on the right hand daily pages of the *Nautical Almanac*.

The sign of the equation of time is positive if the time of sun's meridian passage is earlier than 1200 and negative if later than 1200. Therefore: Apparent Time = Mean Time – (equation of time).

Example 1: *Determine the time of the sun's meridian passage (Local Apparent Noon) on June 16, 1994.*

Solution: *See Figure 2007 in Chapter 20, the Nautical Almanac's right hand daily page for June 16, 1994. The equation of time is listed in the bottom right hand corner of the page. There are two ways to solve the problem, depending on the accuracy required for the value of meridian passage. The time of the sun at meridian passage is given to the nearest minute in the "Mer. Pass."column. For June 16, 1994, this value is 1201.*

To determine the exact time of meridian passage, use the value given for the equation of time. This value is listed immediately to the left of the "Mer. Pass." column on the daily pages. For June 16, 1994, the value is given as 00^m37^s. *Use the "*12^h*" column because the problem asked for meridian passage at LAN. The value of meridian passage from the "Mer. Pass." column indicates that meridian passage occurs after 1200; therefore, add the 37 second correction to 1200 to obtain the exact time of meridian passage. The exact time of meridian passage for June 16, 1994, is* $12^h00^m37^s$.

The equation of time's maximum value approaches 16^m22^s in November.

If the Almanac lists the time of meridian passage as 1200, proceed as follows. Examine the equations of time listed in the Almanac to find the dividing line marking where the equation of time changes between positive and negative values. Examine the trend of the values near this dividing line to determine the correct sign for the equation of time.

Example 2: *See Figure 1801. Determine the time of the upper meridian passage of the sun on April 16, 1995.*

Solution: *From Figure 1801, upper meridian passage of the sun on April 16, 1995, is given as 1200. The dividing line between the values for upper and lower meridian passage on April 16th indicates that the sign of the equation of time changes between lower meridian passage and upper meridian passage on this date; the question, therefore, becomes: does it become positive or negative? Note that on April 18, 1995, upper meridian passage is given as 1159, indicating that on April 18, 1995, the equation of time is positive. All values for the equation of time on the same side of the dividing line as April 18th are positive. Therefore, the equation of time for upper meridian passage of the sun on April 16, 1995 is (+)* 00^m05^s. *Upper meridian passage, therefore, takes place at* $11^h59^m55^s$.

Day	SUN Eqn. of Time 00^h	SUN Eqn. of Time 12^h	SUN Mer. Pass.	MOON Mer. Pass. Upper	MOON Mer. Pass. Lower	MOON Age	MOON Phase
	m s	m s	h m	h m	h m	d	
16	00 02	00 05	12 00	00 26	12 55	16	
17	00 13	00 20	12 00	01 25	13 54	17	
18	00 27	00 33	11 59	02 25	14 55	18	

Figure 1801. The equation of time for April 16, 17, 18, 1995.

To calculate latitude and longitude at LAN, the navigator seldom requires the time of meridian passage to accuracies greater than one minute. Therefore, use the time listed under the "Mer. Pass." column to estimate LAN unless extraordinary accuracy is required.

1802. Fundamental Systems Of Time

The first fundamental system of time is **Ephemeris Time (ET)**. Ephemeris Time is used by astronomers in calculating the fundamental ephemerides of the sun, moon, and planets. It is not used by navigators.

The fundamental system of time of most interest to navigators is **Universal Time (UT)**. UT is the mean solar time on the Greenwich meridian, reckoned in days of 24 mean solar hours beginning with 0^h at midnight. Universal Time, in principle, is determined by the average rate of the apparent daily motion of the sun relative to the meridian of Greenwich; but in practice the numerical measure of Universal Time at any instant is computed from sidereal time. Universal Time is the standard in the application of astronomy to navigation. Observations of Universal Times are made by observing the times of transit of stars.

The Universal Time determined directly from astronomical observations is denoted **UT0**. Since the earth's rotation is nonuniform, corrections must be applied to UT0 to obtain a more uniform time. This more uniform time is obtained by correcting for two known periodic motions.

One motion, the motion of the geographic poles, is the result of the axis of rotation continuously moving with re-

spect to the earth's crust. The corrections for this motion are quite small (± 15 milliseconds for Washington, D.C.). On applying the correction to UT0, the result is **UT1**, which is the same as Greenwich mean time (GMT) used in celestial navigation.

The second known periodic motion is the variation in the earth's speed of rotation due to winds, tides, and other phenomena. As a consequence, the earth suffers an annual variation in its speed of rotation, of about ± 30 milliseconds. When UT1 is corrected for the mean seasonal variations in the earth's rate of rotation, the result is **UT2**.

Although UT2 was at one time believed to be a uniform time system, it was later determined that there are variations in the earth's rate of rotation, possibly caused by random accumulations of matter in the convection core of the earth. Such accumulations would change the earth's moment of inertia and thus its rate of rotation.

The third fundamental system of time, **Atomic Time (AT)**, is based on transitions in the atom. The basic principle of the atomic clock is that electromagnetic waves of a particular frequency are emitted when an atomic transition occurs. The frequency of the cesium beam atomic clock is 9,192,631,770 cycles per second of Ephemeris Time.

The advent of atomic clocks having accuracies better than 1 part in 10^{-13} led in 1961 to the coordination of time and frequency emissions of the U. S. Naval Observatory and the Royal Greenwich Observatory. The master oscillators controlling the signals were calibrated in terms of the cesium standard, and corrections determined at the U. S. Naval Observatory and the Royal Greenwich Observatory were made simultaneously at all transmitting stations. The result is **Coordinated Universal Time (UTC)**.

1803. Time And Arc

One day represents one complete rotation of the earth. Each day is divided into 24 hours of 60 minutes; each minute has 60 seconds.

Time of day is an indication of the phase of rotation of the earth. That is, it indicates how much of a day has elapsed, or what part of a rotation has been completed. Thus, at zero hours the day begins. One hour later, the earth has turned through 1/24 of a day, or 1/24 of 360°, or 360° ÷ 24 = 15°

Smaller intervals can also be stated in angular units; since 1 hour or 60 minutes is equivalent to 15°, 1 minute of time is equivalent to 15° ÷ 60 = 0.25° = 15', and 1 second of time is equivalent to 15' ÷ 60 = 0.25' = 15".

Summarizing in table form:

	Time	Arc
1^d	$=24^h$	=360°
60^m	$=1^h$	=15°
4^m	= 1°	=60'
60^s	$= 1^m$	= 15'
4^s	= 1'	= 60"
1^s	= 15"	= 0.25'

Therefore any time interval can be expressed as an equivalent amount of rotation, and vice versa. Interconversion of these units can be made by the relationships indicated above.

To convert time to arc:

1. Multiply the hours by 15 to obtain degrees of arc.
2. Divide the minutes of time by four to obtain degrees.
3. Multiply the remainder of step 2 by 15 to obtain minutes of arc.
4. Divide the seconds of time by four to obtain minutes of arc
5. Multiply the remainder by 15 to obtain seconds of arc.
6. Add the resulting degrees, minutes, and seconds.

Example 1: *Convert $14^h21^m39^s$ to arc.*

Solution:

(1)	$14^h \times 15$	=	*210° 00' 00"*
(2)	$21^m \div 4$	=	*005° 00' 00" (remainder 1)*
(3)	1×15	=	*000° 15' 00"*
(4)	$39^s \div 4$	=	*000° 09' 00" (remainder 3)*
(5)	3×15	=	*000° 00' 45"*
(6)	$14^h21^m39^s$	=	*215° 24' 45"*

To convert arc to time:

1. Divide the degrees by 15 to obtain hours.
2. Multiply the remainder from step 1 by four to obtain minutes of time.
3. Divide the minutes of arc by 15 to obtain minutes of time.
4. Multiply the remainder from step 3 by four to obtain seconds of time.
5. Divide the seconds of arc by 15 to obtain seconds of time.
6. Add the resulting hours, minutes, and seconds.

Example 2: *Convert 215° 24' 45" to time units.*

Solution:

(1)	215° ÷ 15	=	$14^h00^m00^s$	*remainder 5*
(2)	5×4	=	$00^h20^m00^s$	
(3)	24' ÷ 15	=	$00^h01^m00^s$	*remainder 9*
(4)	9×4	=	$00^h00^m36^s$	

(5) $45'' \div 15 = 00^h00^m03^s$

(6) $215° 24' 45'' = 14^h21^m39^s$

Solutions can also be made using arc to time conversion tables in the almanacs. In the *Nautical Almanac*, the table given near the back of the volume is in two parts, permitting separate entries with degrees, minutes, and quarter minutes of arc. This table is arranged in this manner because the navigator converts arc to time more often than the reverse.

Example 3: *Convert 334°18'22" to time units, using the Nautical Almanac arc to time conversion table.*

Solution:

Convert the 22" to the nearest quarter minute of arc for solution to the nearest second of time. Interpolate if more precise results are required.

$334° 00.00^m = 22^h16^m00^s$
$000° 18.25^m = 00^h01^m13^s$

$334° 18' 22'' = 22^h17^m13^s$

1804. Time And Longitude

Suppose a celestial reference point were directly over a certain point on the earth. An hour later the earth would have turned through 15°, and the celestial reference would be directly over a meridian 15° farther west. Any difference of longitude between two points is a measure of the angle through which the earth must rotate to separate them. Therefore, places east of an observer have later time, and those west have earlier time, and the difference is exactly equal to the difference in longitude, expressed in *time* units. The difference in time between two places is equal to the difference of longitude between their meridians, expressed in time units instead of arc.

1805. The Date Line

Since time is later toward the east and earlier toward the west of an observer, time at the lower branch of one's meridian is 12 hours earlier or later depending upon the direction of reckoning. A traveler making a trip around the world gains or loses an entire day. To prevent the date from being in error, and to provide a starting place for each day, a **date line** is fixed by international agreement. This line coincides with the 180th meridian over most of its length. In crossing this line, the date is altered by one day. If a person is traveling eastward from east longitude to west longitude, time is becoming later, and when the date line is crossed the date becomes 1 day earlier. At any moment the date immediately to the west of the date line (east longitude) is 1 day later than the date immediately to the east of the line. When solving problems, convert local time to Greenwich time and then convert this to local time on the opposite side of the date line.

1806. Zone Time

At sea, as well as ashore, watches and clocks are normally set to some form of **zone time (ZT)**. At sea the nearest meridian exactly divisible by 15° is usually used as the **time meridian** or **zone meridian**. Thus, within a time zone extending 7.5' on each side of the time meridian the time is the same, and time in consecutive zones differs by exactly one hour. The time is changed as convenient, usually at a whole hour, when crossing the boundary between zones. Each time zone is identified by the number of times the longitude of its zone meridian is divisible by 15°, *positive in west longitude* and *negative in east longitude*. This number and its sign, called the **zone description (ZD)**, is the number of whole hours that are added to or subtracted from the zone time to obtain Greenwich mean time (GMT). The mean sun is the celestial reference point for zone time. See Figure 1806.

Converting ZT to GMT, a positive ZT is added and a negative one subtracted; converting GMT to ZT, a positive ZD is subtracted, and a negative one added.

Example: *The GMT is* $15^h27^m09^s$.

Required: *(1) ZT at long. 156°24.4' W.*
(2) ZT at long. 039°04.8' E.

Solutions:

(1)	*GMT*	$15^h27^m09^s$
	ZD	$+10^h$ *(rev.)*
	ZT	$05^h27^m09^s$
(2)	*GMT*	$15^h27^m09^s$
	ZD	-03^h *(rev.)*
	ZT	$18^h27^m09^s$

1807. Chronometer Time

Chronometer time (C) is time indicated by a chronometer. Since a chronometer is set approximately to GMT and not reset until it is overhauled and cleaned about every 3 years, there is nearly always a **chronometer error (CE)**, either fast (F) or slow (S). The change in chronometer error in 24 hours is called **chronometer rate**, or **daily rate**, and designated gaining or losing. With a consistent rate of 1^s per day for three years, the chronometer error would be approximately 18^m. Since chronometer error is subject to change, it should be determined from time to time, preferably daily at sea. Chronometer error is found by radio time signal, by

TIME ZONE CHART

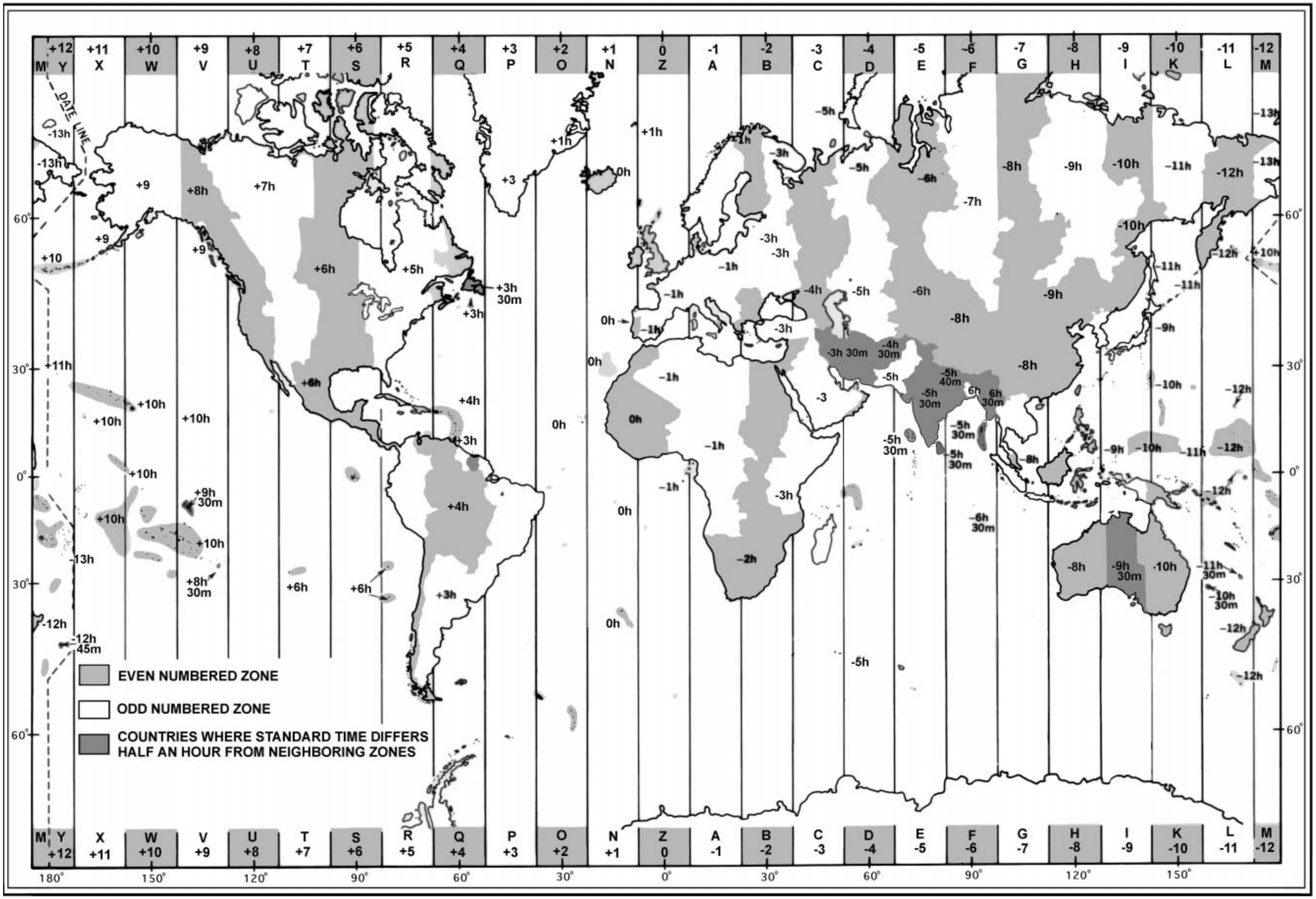


Figure 1806. Time Zone Chart.

comparison with another timepiece of known error, or by applying chronometer rate to previous readings of the same instrument. It is recorded to the nearest whole or half second. Chronometer rate is recorded to the nearest 0.1 second.

Example: *At GMT 1200 on May 12 the chronometer reads* $12^h04^m21^s$*. At GMT 1600 on May 18 it reads* $4^h04^m25^s$*.*

Required: *1. Chronometer error at 1200 GMT May 12.*
2. Chronometer error at 1600 GMT May 18.
3. Chronometer rate.
4. Chronometer error at GMT 0530, May 27.

Solutions:

1.	*GMT*	$12^h00^m00^s$	*May 12*
	C	$12^h04^m21^s$	
	CE	*(F)*4^m21^s	
2.	*GMT*	$16^h00^m00^s$	*May 18*
	C	*04 04 25*	
	CE	*(F)*4^m25^s	
3.	*GMT*	18^d16^h	
	GMT	12^d12h	
	diff.	$06^d04^h = 6.2^d$	
	CE	*(F)*4^m21^s	*1200 May 12*
	CE	*(F)*4^m25^s	*1600 May 18*
	diff.	4^s *(gained)*	
	daily rate	0.6^s *(gain)*	
4.	*GMT*	$27^d05^h30^m$	
	GMT	$18^d16^h00^m$	
	diff.	$08^d13^h30^m$ *(*8.5^d*)*	
	CE	*(F)*4^m25^s	*1600 May 18*
	corr.	*(+)*0^m05^s	*diff. × rate*
	CE	*(F)*4^m30^s	*0530 May 27*

Because GMT is on a 24-hour basis and chronometer time on a 12-hour basis, a 12-hour ambiguity exists. This is ignored in finding chronometer error. However, if chronometer error is applied to chronometer time to find GMT, a 12-hour error can result. This can be resolved by mentally applying the zone description to local time to obtain approximate GMT. A time diagram can be used for resolving doubt as to approximate GMT and Greenwich date. If the sun for the kind of time used (mean or apparent) is between the lower branches of two time meridians (as the standard meridian for local time, and the Greenwich meridian for GMT), the date at the place farther east is one day later than at the place farther west.

1808. Watch Time

Watch time (WT) is usually an approximation of zone time, except that for timing celestial observations it is easiest to set a comparing watch to GMT. If the watch has a second-setting hand, the watch can be set exactly to ZT or GMT, and the time is so designated. If the watch is not set exactly to one of these times, the difference is known as **watch error (WE)**, labeled fast (F) or slow (S) to indicate whether the watch is ahead of or behind the correct time.

If a watch is to be set exactly to ZT or GMT, set it to some whole minute slightly ahead of the correct time and stopped. When the set time arrives, start the watch and check it for accuracy.

The GMT may be in error by 12^h, but if the watch is graduated to 12 hours, this will not be reflected. If a watch with a 24-hour dial is used, the actual GMT should be determined.

To determine watch error compare the reading of the watch with that of the chronometer at a selected moment. This may also be at some selected GMT. Unless a watch is graduated to 24 hours, its time is designated am before noon and pm after noon.

Even though a watch is set to zone time approximately, its error on GMT can be determined and used for timing observations. In this case the 12-hour ambiguity in GMT should be resolved, and a time diagram used to avoid error. This method requires additional work, and presents a greater probability of error, without compensating advantages.

If a stopwatch is used for timing observations, it should be started at some convenient GMT, such as a whole 5^m or 10^m. The time of each observation is then the GMT plus the watch time. Digital stopwatches and wristwatches are ideal for this purpose, as they can be set from a convenient GMT and read immediately after the altitude is taken.

1809. Local Mean Time

Local mean time (LMT), like zone time, uses the mean sun as the celestial reference point. It differs from zone time in that the local meridian is used as the terrestrial reference, rather than a zone meridian. Thus, the local mean time at each meridian differs from every other meridian, the difference being equal to the difference of longitude expressed in time units. At each zone meridian, including 0°, LMT and ZT are identical.

In navigation the principal use of LMT is in rising, setting, and twilight tables. The problem is usually one of converting the LMT taken from the table to ZT. At sea, the difference between the times is normally not more than 30^m, and the conversion is made directly, without finding GMT as an intermediate step. This is done by applying a correction equal to the difference of longitude. If the observer is west of the time meridian, the correction is added, and if east of it, the correction is subtracted. If Greenwich time is desired, it is found from ZT.

Where there is an irregular zone boundary, the longitude may differ by more than 7.5° (30^m) from the time meridian.

If LMT is to be corrected to daylight saving time, the

difference in longitude between the local and time meridian can be used, or the ZT can first be found and then increased by one hour.

Conversion of ZT (including GMT) to LMT is the same as conversion in the opposite direction, except that the sign of difference of longitude is reversed. This problem is not normally encountered in navigation.

1810. Sidereal Time

Sidereal time uses the first point of Aries (vernal equinox) as the celestial reference point. Since the earth revolves around the sun, and since the direction of the earth's rotation and revolution are the same, it completes a rotation with respect to the stars in less time (about $3^m56.6^s$ of mean solar units) than with respect to the sun, and during one revolution about the sun (1 year) it makes one complete rotation more with respect to the stars than with the sun. This accounts for the daily shift of the stars nearly 1° westward each night. Hence, sidereal days are shorter than solar days, and its hours, minutes, and seconds are correspondingly shorter. Because of nutation, sidereal time is not quite constant in rate. Time based upon the average rate is called **mean sidereal time**, when it is to be distinguished from the slightly irregular sidereal time. The ratio of mean solar time units to mean sidereal time units is 1:1.00273791.

A navigator very seldom uses sidereal time. Astronomers use it to regulate mean time because its celestial reference point remains almost fixed in relation to the stars.

1811. Time And Hour Angle

Both time and hour angle are a measure of the phase of rotation of the earth, since both indicate the angular distance of a celestial reference point west of a terrestrial reference meridian. Hour angle, however, applies to any point on the celestial sphere. Time might be used in this respect, but only the apparent sun, mean sun, the first point of Aries, and occasionally the moon, are commonly used.

Hour angles are usually expressed in arc units, and are measured from the upper branch of the celestial meridian. Time is customarily expressed in time units. Sidereal time is measured from the upper branch of the celestial meridian, like hour angle, but solar time is measured from the lower branch. Thus, LMT = LHA mean sun plus or minus 180°, LAT = LHA apparent sun plus or minus 180°, and LST = LHA Aries.

As with time, local hour angle (LHA) at two places differs by their difference in longitude, and LHA at longitude 0° is called Greenwich hour angle (GHA). In addition, it is often convenient to express hour angle in terms of the shorter arc between the local meridian and the body. This is similar to measurement of longitude from the Greenwich meridian. Local hour angle measured in this way is called meridian angle (t), which is labeled east or west, like longitude, to indicate the direction of measurement. A westerly meridian angle is numerically equal to LHA, while an easterly meridian angle is equal to 360° – LHA. LHA = t (W), and LHA = 360° – t (E). Meridian angle is used in the solution of the navigational triangle.

Example: *Find LHA and t of the sun at GMT $3^h24^m16^s$ on June 1, 1975, for long. 118°48.2' W.*

Solution:

GMT	*$3^h24^m16^s$*	*June 1*
3^h	*225°35.7'*	
24^m16^s	*6°04.0'*	
GHA	*231°39.7'*	
λ	*118°48.2'* W	
LHA	*112°51.5'*	
t	*112°51.5' W*	

RADIO DISSEMINATION OF TIME SIGNALS

1812. Dissemination Systems

Of the many systems for time and frequency dissemination, the majority employ some type of radio transmission, either in dedicated time and frequency emissions or established systems such as radionavigation systems. The most accurate means of time and frequency dissemination today is by the mutual exchange of time signals through communication (commonly called Two-Way) and by the mutual observation of navigation satellites (commonly called Common View).

Radio time signals can be used either to perform a clock's function or to set clocks. When using a radio wave instead of a clock, however, new considerations evolve. One is the delay time of approximately 3 microseconds per kilometer it takes the radio wave to propagate and arrive at the reception point. Thus, a user 1,000 kilometers from a transmitter receives the time signal about 3 milliseconds later than the on-time transmitter signal. If time is needed to better than 3 milliseconds, a correction must be made for the time it takes the signal to pass through the receiver.

In most cases standard time and frequency emissions as received are more than adequate for ordinary needs. However, many systems exist for the more exacting scientific requirements.

1813. Characteristic Elements Of Dissemination Systems

A number of common elements characterize most time and frequency dissemination systems. Among the more important elements are accuracy, ambiguity, repeatability, coverage, availability of time signal, reliability, ease of use, cost to the user, and the number of users

served. No single system incorporates all desired characteristics. The relative importance of these characteristics will vary from one user to the next, and the solution for one user may not be satisfactory to another. These common elements are discussed in the following examination of a hypothetical radio signal.

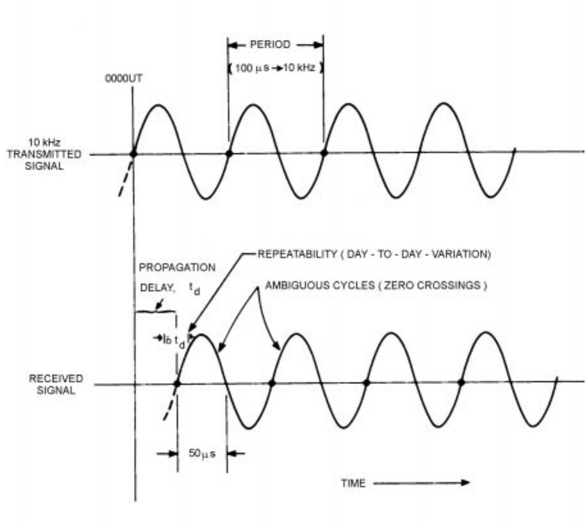


Figure 1813. Single tone time dissemination.

Consider a very simple system consisting of an unmodulated 10-kHz signal as shown in Figure 1813. This signal, leaving the transmitter at 0000 UTC, will reach the receiver at a later time equivalent to the propagation delay. The user must know this delay because the accuracy of his knowledge of time can be no better than the degree to which the delay is known. Since all cycles of the signal are identical, the signal is ambiguous and the user must somehow decide which cycle is the "on time" cycle. This means, in the case of the hypothetical 10-kHz signal, that the user must know the time to ± 50 microseconds (half the period of the signal). Further, the user may desire to use this system, say once a day, for an extended period of time to check his clock or frequency standard. However, if the delay varies from one day to the next without the user knowing, accuracy will be limited by the lack of repeatability.

Many users are interested in making time coordinated measurements over large geographic areas. They would like all measurements to be referenced to one time system to eliminate corrections for different time systems used at scattered or remote locations. This is a very important practical consideration when measurements are undertaken in the field. In addition, a one-reference system, such as a single time broadcast, increases confidence that all measurements can be related to each other in some known way. Thus, the coverage of a system is an important concept. Another important characteristic of a timing system is the percent of time available. The man on the street who has to keep an appointment needs to know the time perhaps to a minute or so. Although requiring only coarse time information, he wants it on demand, so he carries a wristwatch that gives the time 24 hours a day. On the other hand, a user who needs time to a few microseconds employs a very good clock which only needs an occasional update, perhaps only once or twice a day. An additional characteristic of time and frequency dissemination is reliability, i.e., the likelihood that a time signal will be available when scheduled. Propagation fadeout can sometimes prevent reception of HF signals.

1814. Radio Propagation Factors

Radio has been used to transmit standard time and frequency signals since the early 1900's. As opposed to the physical transfer of time via portable clocks, the transfer of information by radio entails propagation of electromagnetic energy through some propagation medium from a transmitter to a distant receiver.

In a typical standard frequency and time broadcast, the signals are directly related to some master clock and are transmitted with little or no degradation in accuracy. In a vacuum and with a noise free background, the signals should be received at a distant point essentially as transmitted, except for a constant path delay with the radio wave propagating near the speed of light (299,773 kilometers per second). The propagation media, including the earth, atmosphere, and ionosphere, as well as physical and electrical characteristics of transmitters and receivers, influence the stability and accuracy of received radio signals, dependent upon the frequency of the transmission and length of signal path. Propagation delays are affected in varying degrees by extraneous radiations in the propagation media, solar disturbances, diurnal effects, and weather conditions, among others.

Radio dissemination systems can be classified in a number of different ways. One way is to divide those carrier frequencies low enough to be reflected by the ionosphere (below 30 MHz) from those sufficiently high to penetrate the ionosphere (above 30 MHz). The former can be observed at great distances from the transmitter but suffer from ionospheric propagation anomalies that limit accuracy; the latter are restricted to line-of-sight applications but show little or no signal deterioration caused by propagation anomalies. The most accurate systems tend to be those which use the higher, line-of-sight frequencies, while broadcasts of the lower carrier frequencies show the greatest number of users.

1815. Standard Time Broadcasts

The World Administrative Radio Council (WARC) has allocated certain frequencies in five bands for standard frequency and time signal emission. For such dedicated standard frequency transmissions, the International Radio Consultative Committee (CCIR) recommends that carrier frequencies be maintained so that the average daily fractional frequency deviations from the internationally

designated standard for measurement of time interval should not exceed 1 X 10^{-10}. The U. S. Naval Observatory Time Service Announcement Series 1, No. 2, gives characteristics of standard time signals assigned to allocated bands, as reported by the CCIR.

1816. Time Signals

The usual method of determining chronometer error and daily rate is by radio time signals, popularly called **time ticks**. Most maritime nations broadcast time signals several times daily from one or more stations, and a vessel equipped with radio receiving equipment normally has no difficulty in obtaining a time tick anywhere in the world. Normally, the time transmitted is maintained virtually uniform with respect to atomic clocks. The Coordinated Universal Time (UTC) as received by a vessel may differ from (GMT) by as much as 0.9 second.

The majority of radio time signals are transmitted automatically, being controlled by the standard clock of an astronomical observatory or a national measurement standards laboratory. Absolute reliance may be had in these signals because they are required to be accurate to at least 0.001^s as transmitted.

Other radio stations, however, have no automatic transmission system installed, and the signals are given by hand. In this instance the operator is guided by the standard clock at the station. The clock is checked by astronomical observations or radio time signals and is normally correct to 0.25 second.

At sea, a spring-driven chronometer should be checked daily by radio time signal, and in port daily checks should be maintained, or begun at least three days prior to departure, if conditions permit. Error and rate are entered in the chronometer record book (or record sheet) each time they are determined.

The various time signal systems used throughout the world are discussed in Pub. No. 117, Radio Navigational Aids, and volume 5 of Admiralty List of Radio Signals. Only the United States signals are discussed here.

The National Institute of Standards and Technology (NIST) broadcasts continuous time and frequency reference signals from WWV, WWVH, WWVB, and the GOES satellite system. Because of their wide coverage and relative simplicity, the HF services from WWV and WWVH are used extensively for navigation.

Station WWV broadcasts from Fort Collins, Colorado at the internationally allocated frequencies of 2.5, 5.0, 10.0, 15.0, and 20.0 MHz; station WWVH transmits from Kauai, Hawaii on the same frequencies with the exception of 20.0 MHz. The broadcast signals include standard time and frequencies, and various voice announcements. Details of these broadcasts are given in NIST Special Publication 432, *NIST Frequency and Time Dissemination Services*. Both HF emissions are directly controlled by cesium beam frequency standards with periodic reference to the NIST atomic frequency and time standards.

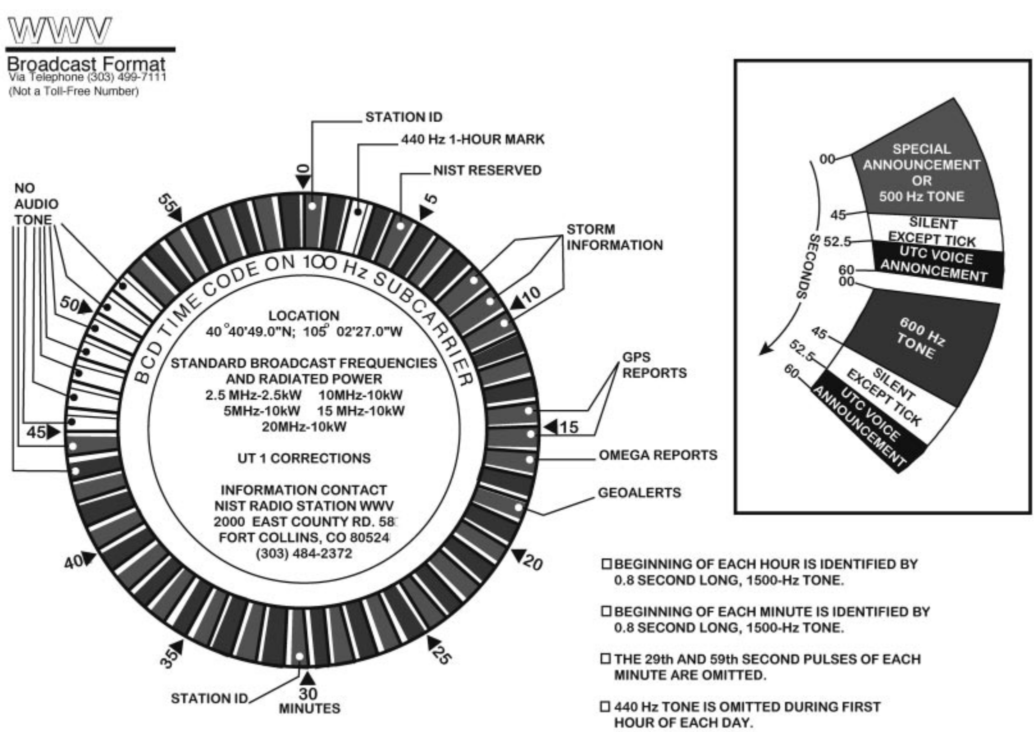


Figure 1816a. Broadcast format of station WWV.

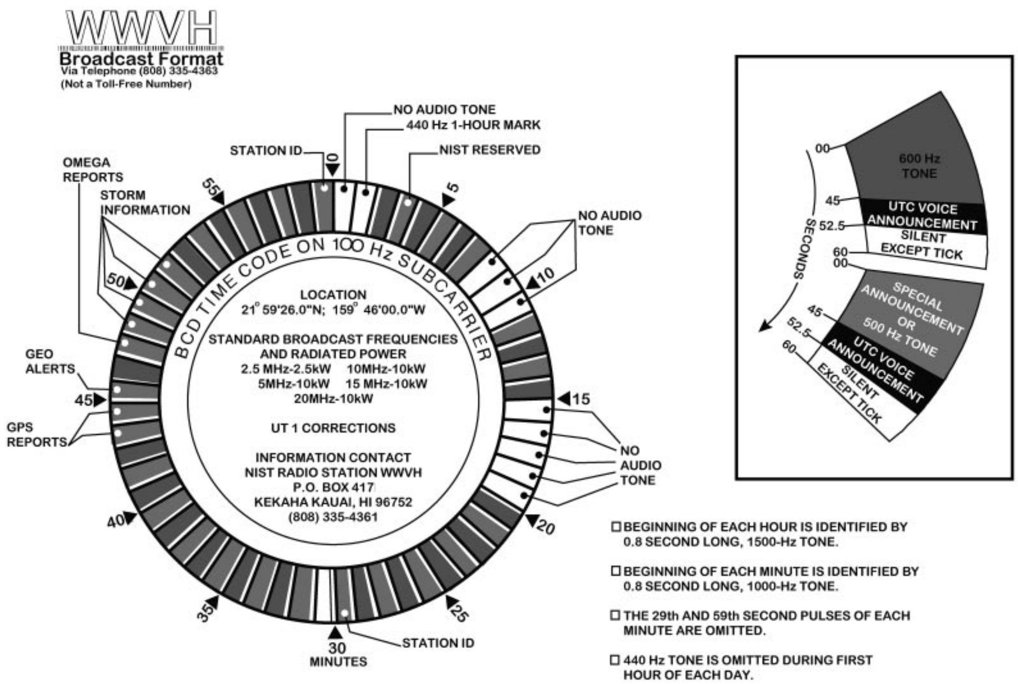


Figure 1816b. Broadcast format of station WWVH.

The time ticks in the WWV and WWVH emissions are shown in Figure 1816a and Figure 1816b. The 1-second UTC markers are transmitted continuously by WWV and WWVH, except for omission of the 29th and 59th marker each minute. With the exception of the beginning tone at each minute (800 milliseconds) all 1-second markers are of 5 milliseconds duration. Each pulse is preceded by 10 milliseconds of silence and followed by 25 milliseconds of silence. Time voice announcements are given also at 1-minute intervals. All time announcements are UTC.

Pub. No. 117, Radio Navigational Aids, should be referred to for further information on time signals.

1817. Leap-Second Adjustments

By international agreement, UTC is maintained within about 0.9 seconds of the celestial navigator's time scale, UT1. The introduction of **leap seconds** allows a good clock to keep approximate step with the sun. Because of the variations in the rate of rotation of the earth, however, the occurrences of the leap seconds are not predictable in detail.

The Central Bureau of the International Earth Rotation Service (IERS) decides upon and announces the introduction of a leap second. The IERS announces the new leap second at least several weeks in advance. A positive or negative leap

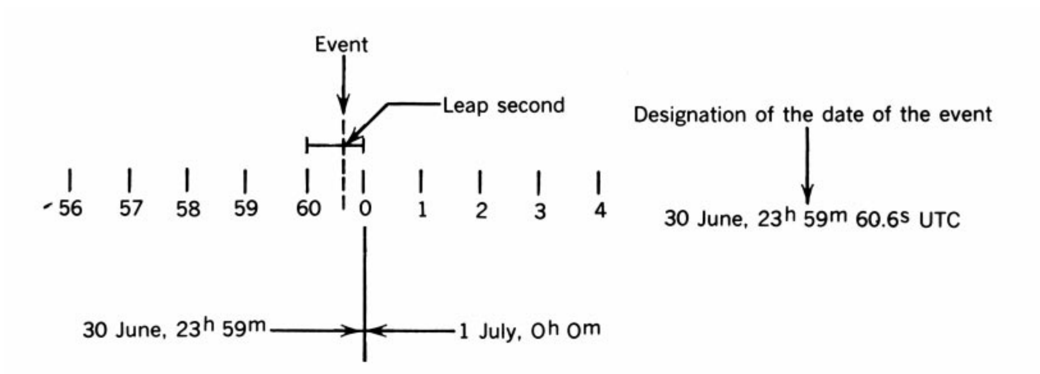


Figure 1817a. Dating of event in the vicinity of a positive leap second.

second is introduced the last second of a UTC month, but first preference is given to the end of December and June, and second preference is given to the end of March and September. A positive leap second begins at $23^h59^m60^s$ and ends at $00^h00^m00^s$ of the first day of the following month. In the case of a negative leap second, $23^h59^m58^s$ is followed one second later by $00^h00^m00^s$ of the first day of the following month.

The dating of events in the vicinity of a leap second is effected in the manner indicated in Figure 1817a and Figure 1817b.

Whenever leap second adjustments are to be made to UTC, mariners are advised by messages from the Defense Mapping Agency Hydrographic/Topographic Center.

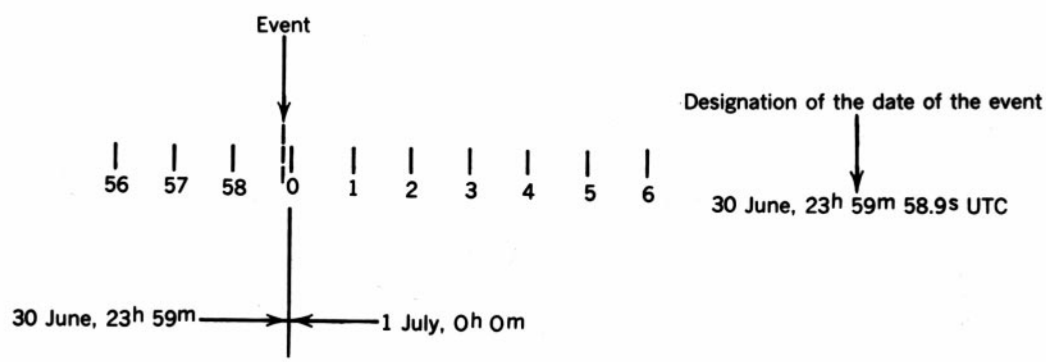


Figure 1817b. Dating of event in the vicinity of a negative leap second.

CHAPTER 19

THE ALMANACS

PURPOSE OF ALMANACS

1900. Introduction

Celestial navigation requires accurate predictions of the geographic positions of the celestial bodies observed. These predictions are available from three almanacs published annually by the United States Naval Observatory and H. M. Nautical Almanac Office, Royal Greenwich Observatory.

The ***Astronomical Almanac*** precisely tabulates celestial data for the exacting requirements found in several scientific fields. Its precision is far greater than that required by celestial navigation. Even if the *Astronomical Almanac* is used for celestial navigation, it will not necessarily result in more accurate fixes due to the limitations of other aspects of the celestial navigation process.

The ***Nautical Almanac*** contains the astronomical information specifically needed by marine navigators. Information is tabulated to the nearest 0.1' of arc and 1 second of time. GHA and declination are available for the sun, moon, planets, and 173 stars, as well as corrections necessary to reduce the observed values to true.

The ***Air Almanac*** is intended primarily for air navigators. In general, the information is similar to the *Nautical Almanac*, but is given to a precision of 1' of arc and 1 second of time, at intervals of 10 minutes (values for the sun and Aries are given to a precision of 0.1'). This publication is suitable for ordinary navigation at sea, but may lack the precision of the *Nautical Almanac*, and provides GHA and declination for only the 57 commonly used navigation stars.

The **Floppy Almanac** is a computer software program produced by the U.S. Naval Observatory which not only contains ephemeris data, but also computes rising, setting, and twilight problems; does sight planning given course and speed (this function includes a computer-generated star finder centered on the observer's zenith); computes great circle and rumb line routes; computes compass error from celestial observations; and does complete sight reduction solutions including computer plotting and weighted analysis of the LOP's. The Floppy Almanac is in DOS format.

FORMAT OF THE *NAUTICAL* AND *AIR ALMANACS*

1901. *Nautical Almanac*

The major portion of the *Nautical Almanac* is devoted to hourly tabulations of Greenwich Hour Angle (GHA) and declination, to the nearest 0.1' of arc. On each set of facing pages, information is listed for three consecutive days. On the left-hand page, successive columns list GHA of Aries (♈), and both GHA and declination of Venus, Mars, Jupiter, and Saturn, followed by the Sidereal Hour Angle (SHA) and declination of 57 stars. The GHA and declination of the sun and moon, and the horizontal parallax of the moon, are listed on the right-hand page. Where applicable, the quantities v and d are given to assist in interpolation. The quantity v is the difference between the actual change of GHA in 1 hour and a constant value used in the interpolation tables, while d is the change in declination in 1 hour. Both v and d are listed to the nearest 0.1'.

To the right of the moon data is listed the Local Mean Time (LMT) of sunrise, sunset, and beginning and ending of nautical and civil twilight for latitudes from 72°N to 60°S. The LMT of moonrise and moonset at the same latitudes is listed for each of the three days for which other information is given, and for the following day. Magnitude of each planet at UT 1200 of the middle day is listed at the top of the column. The UT of transit across the celestial meridian of Greenwich is listed as "Mer. Pass.". The value for the first point of Aries for the middle of the three days is listed to the nearest 0.1' at the bottom of the Aries column. The time of transit of the planets for the middle day is given to the nearest whole minute, with SHA (at UT 0000 of the middle day) to the nearest 0.1', below the list of stars. For the sun and moon, the time of transit to the nearest whole minute is given for each day. For the moon, both upper and lower transits are given. This information is tabulated below the rising, setting, and twilight information. Also listed, are the equation of time for 0^h and 12^h, and the age and phase of the moon. Equation of time is listed, without sign, to the nearest whole second. Age is given to the nearest whole day. Phase is given by symbol.

The main tabulation is preceded by a list of religious and civil holidays, phases of the Moon, a calendar, information on eclipses occurring during the year, and notes and a diagram giving information on the planets.

The main tabulation is followed by explanations and examples. Next are four pages of standard times (zone

descriptions). Star charts are next, followed by a list of 173 stars in order of increasing SHA. This list includes the stars given on the daily pages. It gives the SHA and declination-each month, and the magnitude. Stars are listed by Bayer's name and also by popular name where applicable. Following the star list are the Polaris tables. These tables give the azimuth and the corrections to be applied to the observed altitude to find the latitude.

Following the Polaris table is a section that gives formulas and examples for the entry of almanac data, the calculations that reduce a sight, and a method of solution for position, all for use with a calculator or microcomputer. This is followed by concise sight reduction tables, with instructions and examples, for use when a calculator or traditional sight reduction tables are not available. Tabular precision of the concise tables is one minute of arc.

Next is a table for converting arc to time units. This is followed by a 30-page table called "Increments and Corrections," used for interpolation of GHA and declination. This table is printed on tinted paper, for quick location. Then come tables for interpolating for times of rise, set, and twilight; followed by two indices of the 57 stars listed on the daily pages, one index in alphabetical order, and the other in order of decreasing SHA.

Sextant altitude corrections are given at the front and back of the almanac. Tables for the sun, stars, and planets, and a dip table, are given on the inside front cover and facing page, with an additional correction for nonstandard temperature and atmospheric pressure on the following page. Tables for the moon, and an abbreviated dip table, are given on the inside back cover and facing page. Corrections for the sun, stars, and planets for altitudes greater than 10°, and the dip table, are repeated on one side of a loose bookmark. The star indices are repeated on the other side.

1902. *Air Almanac*

As in the *Nautical Almanac*, the major portion of the *Air Almanac* is devoted to a tabulation of GHA and declination. However, in the *Air Almanac* values are listed at intervals of 10 minutes, to a precision of 0.1' for the sun and Aries, and to a precision of 1' for the moon and the planets. Values are given for the sun, first point of Aries (GHA only), the three navigational planets most favorably located for observation, and the moon. The magnitude of each planet listed is given at the top of its column, and the phase of the moon is given at the top of its column. Values for the first 12 hours of the day are given on the right-hand page, and those for the second half of the day on the back. In addition, each page has a table of the moon's parallax in altitude, and below this the semidiameter of the sun, and both the semidiameter and age of the moon. Each daily page includes the LMT of moonrise and moonset; and a difference column to find the time of moonrise and moonset at any longitude.

Critical tables for interpolation for GHA are given on the inside front cover, which also has an alphabetical listing of the stars, with the number, magnitude, SHA, and declination of each. The same interpolation table and star list are printed on a flap which follows the daily pages. This flap also contains a star chart, a star index in order of decreasing SHA, and a table for interpolation of the LMT of moonrise and moonset for longitude.

Following the flap are instructions for the use of the almanac; a list of symbols and abbreviations in English, French, and Spanish; a list of time differences between Greenwich and other places; sky diagrams; a planet location diagram; star recognition diagrams for periscopic sextants; sunrise, sunset, and civil twilight tables; rising, setting, and depression graphs; semiduration graphs of sunlight, twilight, and moonlight in high latitudes; percentage of the moon illuminated at 6 and 18 hours UT daily; a list of 173 stars by number and Bayer's name (also popular name where there is one), giving the SHA and declination each month (to a precision of 0.1'), and the magnitude; tables for interpolation of GHA sun and GHA ♈ ; a table for converting arc to time; a single Polaris correction table; an aircraft standard dome refraction table; a refraction correction table; a Coriolis correction table; and on the inside back cover, a correction table for dip of the horizon.

USING THE ALMANACS

1903. Entering Arguments

The time used as an entering argument in the almanacs is 12^h + GHA of the mean sun and is denoted by UT. This scale may differ from the broadcast time signals by an amount which, if ignored, will introduce an error of up to 0.2' in longitude determined from astronomical observations. The difference arises because the time argument depends on the variable rate of rotation of the earth while the broadcast time signals are now based on atomic time. Step adjustments of exactly one second are made to the time signals as required (primarily at 24h on December 31 and June 30) so that the

Correction to time signals	*Correction to longitude*
-0.7^s to -0.9^s	0.2' to east
-0.6^s to -0.3^s	0.1' to east
-0.2^s to $+0.2^s$	no correction
$+0.3^s$ to $+0.6^s$	0.1' to west
$+0.7^s$ to $+0.9^s$	0.2' to west

Table 1903. Corrections to time.

difference between the time signals and UT, as used in the almanacs, may not exceed 0.9^s. If observations to a precision of better than 1^s are required, corrections must be obtained from coding in the signal, or from other sources. The correction may be applied to each of the times of observation. Alternatively, the longitude, when determined from observations, may be corrected by the corresponding amount shown in Table 1903.

The main contents of the almanacs consist of data from which the GHA and the declination of all the bodies used for navigation can be obtained for any instant of UT. The LHA can then be obtained with the formula:

LHA = GHA + east longitude.
LHA = GHA - west longitude.

For the sun, moon, and the four navigational planets, the GHA and declination are tabulated directly in the *Nautical Almanac* for each hour of GMT throughout the year; in the *Air Almanac*, the values are tabulated for each whole 10 m of GMT. For the stars, the SHA is given, and the GHA is obtained from:

GHA Star = GHA ♈ + SHA Star.

The SHA and declination of the stars change slowly and may be regarded as constant over periods of several days or even months if lesser accuracy is required. The SHA and declination of stars tabulated in the *Air Almanac* may be considered constant to a precision of 1.5' to 2' for the period covered by each of the volumes providing the data for a whole year, with most data being closer to the smaller value. GHA ♈, or the GHA of the first point of Aries (the vernal equinox), is tabulated for each hour in the *Nautical Almanac* and for each whole 10^m in the *Air Almanac*. Permanent tables list the appropriate increments to the tabulated values of GHA and declination for the minutes and seconds of time.

In the *Nautical Almanac*, the permanent table for increments also includes corrections for *v*, the difference between the actual change of GHA in one hour and a constant value used in the interpolation tables; and *d*, the change in declination in one hour.

In the *Nautical Almanac*, *v* is always positive unless a negative sign (-) is shown. This occurs only in the case of Venus. For the sun, the tabulated values of GHA have been adjusted to reduce to a minimum the error caused by treating *v* as negligible; there is no *v* tabulated for the sun.

No sign is given for tabulated values of *d*, which is positive if declination is increasing, and negative if decreasing. The sign of a *v* or *d* value is also given to the related correction.

In the *Air Almanac*, the tabular values of the GHA of the moon are adjusted so that use of an interpolation table based on a fixed rate of change gives rise to negligible error; no such adjustment is necessary for the sun and planets. The tabulated declination values, except for the sun, are those for the middle of the interval between the time indicated and the next following time for which a value is given, making interpolation unnecessary. Thus, it is always important to take out the GHA and declination for the time immediately *before* the time of observation.

In the *Air Almanac*, GHA ♈ and the GHA and declination of the sun are tabulated to a precision of 0.1'. If these values are extracted with the tabular precision, the "Interpolation of GHA" table on the inside front cover (and flap) should not be used; use the "Interpolation of GHA Sun" and "Interpolation of GHA Aries' tables, as appropriate. These tables are found immediately preceding the Polaris Table.

1904. Finding GHA And Declination Of The Sun

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless the exact time is a whole hour, and take out the tabulated GHA and declination. Also record the d value given at the bottom of the declination column. Next, enter the increments and corrections table for the number of minutes of GMT. If there are seconds, use the next earlier whole minute. On the line corresponding to the seconds of GMT, extract the value from the Sun-Planets column. Add this to the value of GHA from the daily page. This is GHA of the sun. Next, enter the correction table for the same minute with the d value and take out the correction. Give this the sign of the d value and apply it to the declination from the daily page. This is the declination.

The correction table for GHA of the Sun is based upona rate of change of 15° per hour, the average rate during a year. At most times the rate differs slightly. The slight error is minimized by adjustment of the tabular values. The d value is the amount that the declination changes between 1200 and 1300 on the middle day of the three shown.

Air Almanac: Enter the daily page with the whole 10^m preceding the given GMT, unless the time is itself a whole 10^m, and extract the GHA. The declination is extracted without interpolation from the same line as the tabulated GHA or, in the case of planets, the top line of the block of six. If the values extracted are rounded to the nearest minute, next enter the "Interpolation of GHA" table on the inside front cover (and flap), using the "Sun, etc." entry column, and take out the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction listed half a line above the entry time. Add this correction to the GHA taken from the daily page. This is GHA. No adjustment of declination is needed. If the values are extracted with a precision of 0.1', the table for interpolating the GHA of the sun to a precision of 0.1' must be used. Again no adjustment of declination is needed.

1905. Finding GHA And Declination Of The Moon

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless this time is itself a whole hour, and extract the tabulated GHA and declination. Record the corresponding v and d values tabulated on

the same line, and determine the sign of the d value. The v value of the moon is always positive (+) and is not marked in the almanac. Next, enter the increments and corrections table for the minutes of GMT, and on the line for the seconds of GMT, take the GHA correction from the moon column. Then, enter the correction table for the same minute with the v value, and extract the correction. Add both of these corrections to the GHA from the daily page. This is GHA of the moon. Then, enter the same correction table with the d value and extract the correction. Give this correction the sign of the d value and apply it to the declination from the daily page. This is declination.

The correction table for GHA of the moon is based upon the minimum rate at which the moon's GHA increases, 14°19.0' per hour. The v correction adjusts for the actual rate. The v value is the difference between the minimum rate and the actual rate during the hour following the tabulated time. The d value is the amount that the declination changes during the hour following the tabulated time.

Air Almanac: Enter the daily page with the whole 10^m next preceding the given GMT, unless this time is a whole 10^m, and extract the tabulated GHA and the declination without interpolation. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "moon" entry column, and extract the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction given half a line above the entry time. Add this correction to the GHA taken from the daily page to find the GHA at the given time. No adjustment of declination is needed.

The declination given in the table is correct for the time 5 minutes later than tabulated, so that it can be used for the 10-minute interval without interpolation, to an accuracy to meet most requirements. Declination changes much more slowly than GHA. If greater accuracy is needed, it can be obtained by interpolation, remembering to allow for the 5 minutes.

1906. Finding GHA And Declination Of A Planet

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless the time is a whole hour, and extract the tabulated GHA and declination. Record the v value given at the bottom of each of these columns. Next, enter the increments and corrections table for the minutes of GMT, and on the line for the seconds of GMT, take the GHA correction from the sun-planets column. Next, enter the correction table with the v value and extract the correction, giving it the sign of the v value. Add the first correction to the GHA from the daily page, and apply the second correction in accordance with its sign. This is GHA. Then enter the correction table for the same minute with the d value, and extract the correction. Give this correction the sign of the d value, and apply it to the declination from the daily page to find the declination at the given time.

The correction table for GHA of planets is based upon the mean rate of the sun, 15° per hour. The v value is the difference between 15° and the change of GHA of the planet between 1200 and 1300 on the middle day of the three shown. The d value is the amount the declination changes between 1200 and 1300 on the middle day. Venus is the only body listed which ever has a negative v value.

Air Almanac: Enter the daily page with the whole 10^m before the given GMT, unless this time is a whole 10^m, and extract the tabulated GHA and declination, without interpolation. The tabulated declination is correct for the time 30^m later than tabulated, so interpolation during the hour following tabulation is not needed for most purposes. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "sun, etc." column, and take out the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction half a line above the entry time. Add this correction to the GHA from the daily page to find the GHA at the given time. No adjustment of declination is needed.

1907. Finding GHA And Declination Of A Star

If the GHA and declination of each navigational star were tabulated separately, the almanacs would be several times their present size. But since the sidereal hour angle and the declination are nearly constant over several days (to the nearest 0.1') or months (to the nearest 1'), separate tabulations are not needed. Instead, the GHA of the first point of Aries, from which SHA is measured, is tabulated on the daily pages, and a single listing of SHA and declination is given for each double page of the Nautical Almanac, and for an entire volume of the Air Almanac. Finding the GHA ♈ is similar to finding the GHA of the sun, moon, and planets.

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless this time is a whole hour, and extract the tabulated GHA of Aries. Also record the tabulated SHA and declination of the star from the listing on the left-hand daily page. Next, enter the increments and corrections table for the minutes of GMT, and, on the line for the seconds of GMT, extract the GHA correction from the Aries column. Add this correction and the SHA of the star to the GHA ♈ on the daily page to find the GHA of the star at the given time. No adjustment of declination is needed.

The SHA and declination of 173 stars, including Polaris and the 57 listed on the daily pages, are given for the middle of each month. For a star not listed on the daily pages, this is the only almanac source of this information. Interpolation in this table is not necessary for ordinary purposes of navigation, but is sometimes needed for precise results.

Air Almanac: Enter the daily page with the whole 10^m before the given GMT, unless this is a whole 10^m, and extract the tabulated GHA ♈. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "Sun, etc." entry column, and extract the value for the remaining minutes and seconds of GMT. If the entry time is an exact

tabulated value, use the correction given half a line above the entry time. From the tabulation at the left side of the same page, extract the SHA and declination of the star. Add the GHA from the daily page and the two values taken from the inside front cover to find the GHA at the given time. No adjustment of declination is needed.

RISING, SETTING, AND TWILIGHT

1908. Rising, Setting, And Twilight

In both *Air* and *Nautical Almanacs*, the times of sunrise, sunset, moonrise, moonset, and twilight information, at various latitudes between 72°N and 60°S, is listed to the nearest whole minute. By definition, rising or setting occurs when the upper limb of the body is on the visible horizon, assuming standard refraction for zero height of eye. Because of variations in refraction and height of eye, computation to a greater precision than 1 minute of time is not justified.

In high latitudes, some of the phenomena do not occur during certain periods. Symbols are used in the almanacs to indicate:

1. Sun or moon does not set, but remains continuously above the horizon, indicated by an open rectangle.
2. Sun or moon does not rise, but remains continuously below the horizon, indicated by a solid rectangle.
3. Twilight lasts all night, indicated by 4 slashes (////).

The *Nautical Almanac* makes no provision for finding the times of rising, setting, or twilight in polar regions. The *Air Almanac* has graphs for this purpose.

In the *Nautical Almanac*, sunrise, sunset, and twilight tables are given only once for the middle of the three days on each page opening. For navigational purposes this information can be used for all three days. Both almanacs have moonrise and moonset tables for each day.

The tabulations are in LMT. On the zone meridian, this is the zone time (ZT). For every 15' of longitude the observer's position differs from the zone meridian, the zone time of the phenomena differs by 1^m, being later if the observer is west of the zone meridian, and earlier if east of the zone meridian. The LMT of the phenomena varies with latitude of the observer, declination of the body, and hour angle of the body relative to the mean sun.

The UT of the phenomenon is found from LMT by the formula:

UT = LMT + W Longitude
UT = LMT - E Longitude.

To use this formula, convert the longitude to time using the table on page i or by computation, and add or subtract as indicated. Apply the zone description (ZD) to find the zone time of the phenomena.

Sunrise and sunset are also tabulated in the tide tables (from 76°N to 60°S).

1909. Finding Times Of Sunrise And Sunset

To find the time of sunrise or sunset in the *Nautical Almanac*, enter the table on the daily page, and extract the LMT for the latitude next smaller than your own (unless it is exactly the same). Apply a correction from Table I on almanac page xxxii to interpolate for altitude, determining the sign by inspection. Then convert LMT to ZT using the difference of longitude between the local and zone meridians.

For the *Air Almanac*, the procedure is the same as for the *Nautical Almanac*, except that the LMT is taken from the tables of sunrise and sunset instead of from the daily page, and the latitude correction is by linear interpolation.

The tabulated times are for the Greenwich meridian. Except in high latitudes near the time of the equinoxes, the time of sunrise and sunset varies so little from day to day that no interpolation is needed for longitude. In high latitudes interpolation is not always possible. Between two tabulated entries, the sun may in fact cease to set. In this case, the time of rising and setting is greatly influenced by small variations in refraction and changes in height of eye.

1910. Twilight

Morning twilight ends at sunrise, and evening twilight begins at sunset. The time of the darker limit can be found from the almanacs. The time of the darker limits of both civil and nautical twilights (center of the sun 6° and 12°, respectively, below the celestial horizon) is given in the *Nautical Almanac*. The *Air Almanac* provides tabulations of civil twilight from 60°S to 72°N. The brightness of the sky at any given depression of the sun below the horizon may vary considerably from day to day, depending upon the amount of cloudiness, haze, and other atmospheric conditions. In general, the most effective period for observing stars and planets occurs when the center of the sun is between about 3° and 9° below the celestial horizon. Hence, the darker limit of civil twilight occurs at about the midpoint of this period. At the darker limit of nautical twilight, the horizon is generally too dark for good observations.

At the darker limit of astronomical twilight (center of the sun 18° below the celestial horizon), full night has set in. The time of this twilight is given in the *Astronomical Almanac*. Its approximate value can be determined by extrapolation in the *Nautical Almanac*, noting that the duration of the different kinds of twilight is not proportional to the number of degrees of depression at the darker limit.

More precise determination of the time at which the center of the sun is any given number of degrees below the celestial horizon can be determined by a large-scale diagram on the plane of the celestial meridian, or by computation. Duration of twilight in latitudes higher than 65°N is given in a graph in the *Air Almanac*.

In both *Nautical* and *Air Almanacs*, the method of finding the darker limit of twilight is the same as that for sunrise and sunset.

Sometimes in high latitudes the sun does not rise but twilight occurs. This is indicated in the *Air Almanac* by a solid black rectangle symbol in the sunrise and sunset column. To find the time of beginning of morning twilight, subtract half the duration of twilight as obtained from the duration of twilight graph from the time of meridian transit of the sun; and for the time of ending of evening twilight, add it to the time of meridian transit. The LMT of meridian transit never differs by more than 16.4^m (approximately) from 1200. The actual time on any date can be determined from the almanac.

1911. Moonrise And Moonset

Finding the time of moonrise and moonset is similar to finding the time of sunrise and sunset, with one important difference. Because of the moon's rapid change of declination, and its fast eastward motion relative to the sun, the time of moonrise and moonset varies considerably from day to day. These changes of position on the celestial sphere are continuous, as moonrise and moonset occur successively at various longitudes around the earth. Therefore, the change in time is distributed over all longitudes. For precise results, it would be necessary to compute the time of the phenomena at any given place by lengthy complex calculation. For ordinary purposes of navigation, however, it is sufficiently accurate to interpolate between consecutive moonrises or moonsets at the Greenwich meridian. Since apparent motion of the moon is westward, relative to an observer on the earth, interpolation in west longitude is between the phenomenon on the given date and the following one. In east longitude it is between the phenomenon on the given date and the preceding one.

To find the time of moonrise or moonset in the *Nautical Almanac*, enter the daily-page table with latitude, and extract the LMT for the tabulated latitude next smaller than the observer's latitude (unless this is an exact tabulated value). Apply a correction from table I of almanac page xxxii to interpolate for latitude, determining the sign of the correction by inspection. Repeat this procedure for the day following the given date, if in west longitude; or for the day preceding, if in east longitude. Using the difference between these two times, and the longitude, enter table II of the almanac on the same page and take out the correction. Apply this correction to the LMT of moonrise or moonset at the Greenwich meridian on the given date to find the LMT at the position of the observer. The sign to be given the correction is such as to make the corrected time fall between the times for the two dates between which interpolation is being made. This is nearly always positive (+) in west longitude and negative (-) in east longitude. Convert the corrected LMT to ZT.

To find the time of moonrise or moonset by the *Air Almanac* for the given date, determine LMT for the observer's latitude at the Greenwich meridian in the same manner as with the *Nautical Almanac*, except that linear interpolation is made directly from the main tables, since no interpolation table is provided. Extract, also, the value from the "Diff." column to the right of the moonrise and moonset column, interpolating if necessary. This "Diff." is one-fourth of one-half of the daily difference. The error introduced by this approximation is generally not more than a few minutes, although it increases with latitude. Using this difference, and the longitude, enter the "Interpolation of Moonrise, Moonset" table on flap F4 of the *Air Almanac* and extract the correction. The *Air Almanac* recommends taking the correction from this table without interpolation. The results thus obtained are sufficiently accurate for ordinary purposes of navigation. If greater accuracy is desired, the correction can be taken by interpolation. However, since the "Diff." itself is an approximation, the *Nautical Almanac* or computation should be used if accuracy is a consideration. Apply the correction to the LMT of moonrise or moonset at the Greenwich meridian on the given date to find the LMT at the position of the observer. The correction is positive (+) for west longitude, and negative (-) for east longitude, unless the "Diff." on the daily page is preceded by the negative sign (-), when the correction is negative (-) for west longitude, and positive (+) for east longitude. If the time is near midnight, record the date at each step, as in the *Nautical Almanac* solution.

As with the sun, there are times in high latitudes when interpolation is inaccurate or impossible. At such periods, the times of the phenomena themselves are uncertain, but an approximate answer can be obtained by the moonlight graph in the *Air Almanac*, or by computation. With the moon, this condition occurs when the moon rises or sets at one latitude, but not at the next higher tabulated latitude, as with the sun. It also occurs when the moon rises or sets on one day, but not on the preceding or following day. This latter condition is indicated in the *Air Almanac* by the symbol * in the "Diff." column.

Because of the eastward revolution of the moon around the earth, there is one day each synodical month (29 $^1/_2$ days) when the moon does not rise, and one day when it does not set. These occur near last quarter and first quarter, respectively. Since this day is not the same at all latitudes or at all longitudes, the time of moonrise or moonset found from the almanac may occasionally be the preceding or succeeding one to that desired. When interpolating near midnight, caution will prevent an error.

The effect of the revolution of the moon around the earth is to cause the moon to rise or set later from day to day. The daily retardation due to this effect does not differ greatly from 50^m. However, the change in declination of the moon

may increase or decrease this effect. This effect increases with latitude, and in extreme conditions it may be greater than the effect due to revolution of the moon. Hence, the interval between successive moonrises or moonsets is more erratic in high latitudes than in low latitudes. When the two effects act in the same direction, daily differences can be quite large. When they act in opposite directions, they are small, and when the effect due to change in declination is larger than that due to revolution, the moon sets *earlier* on succeeding days. This condition is reflected in the *Air Almanac* by a negative “Diff.” If this happens near the last quarter or first quarter, two moonrises or moonsets might occur on the same day, one a few minutes after the day begins, and the other a few minutes before it ends, as on June 19, where two times are listed in the same space.

Interpolation for longitude is always made between consecutive moonrises or moonsets, regardless of the days on which they fall.

Beyond the northern limits of the almanacs the values can be obtained from a series of graphs given near the back of the *Air Almanac*. For high latitudes, graphs are used instead of tables because graphs give a clearer picture of conditions, which may change radically with relatively little change in position or date. Under these conditions interpolation to practical precision is simpler by graph than by table. In those parts of the graph which are difficult to read, the times of the phenomena’s occurrence are uncertain, being altered considerably by a relatively small change in refraction or height of eye.

On all of these graphs, any given latitude is represented by a horizontal line and any given date by a vertical line. At the intersection of these two lines the duration is read from the curves, interpolating by eye between curves.

The “Semiduration of Sunlight” graph gives the number of hours between sunrise and meridian transit or between meridian transit and sunset. The dot scale near the top of the graph indicates the LMT of meridian transit, the time represented by the minute dot nearest the vertical dateline being used. If the intersection occurs in the area marked “sun above horizon,” the sun does not set; and if in the area marked “sun below horizon,” the sun does not rise.

The “Duration of Twilight” graph gives the number of hours between the beginning of morning civil twilight (center of sun 6° below the horizon) and sunrise, or between sunset and the end of evening civil twilight. If the sun does not rise, but twilight occurs, the time taken from the graph is half the total length of the single twilight period, or the number of hours from beginning of morning twilight to LAN, or from LAN to end of evening twilight. If the intersection occurs in the area marked “continuous twilight or sunlight,” the center of the sun does not move more than 6° below the horizon, and if in the area marked “no twilight nor sunlight,” the sun remains more than 6° below the horizon throughout the entire day.

The “Semiduration of Moonlight” graph gives the number of hours between moonrise and meridian transit or between meridian transit and moonset. The dot scale near the top of the graph indicates the LMT of meridian transit, each dot representing one hour. The phase symbols indicate the date on which the principal moon phases occur, the open circle indicating full moon and the dark circle indicating new moon. If the intersection of the vertical dateline and the horizontal latitude line falls in the “moon above horizon” or “moon below horizon” area, the moon remains above or below the horizon, respectively, for the entire 24 hours of the day.

If approximations of the times of moonrise and moonset are sufficient, the semiduration of moonlight is taken for the time of meridian passage and can be used without adjustment. When as estimated time of rise falls on the preceding day, that phenomenon may be recalculated using the meridian passage and semiduration for the day following. When an estimated time of set falls on the following day, that phenomenon may be recalculated using meridian passage and semiduration for the preceding day. For more accurate results (seldom justified), the times on the required date and the adjacent date (the following date in W longitude and the preceding date in E longitude) should be determined, and an interpolation made for longitude, as in any latitude, since the intervals given are for the Greenwich meridian.

Sunlight, twilight, and moonlight graphs are not given for south latitudes. Beyond latitude 65°S, the northern hemisphere graphs can be used for determining the semiduration or duration, by using the vertical dateline for a day when the declination has the same numerical value but opposite sign. The time of meridian transit and the phase of the moon are determined as explained above, using the correct date. Between latitudes 60°S and 65°S, the solution is made by interpolation between the tables and the graphs.

Other methods of solution of these phenomena are available. The Tide Tables tabulate sunrise and sunset from latitude 76°N to 60°S. Semiduration or duration can be determined graphically using a diagram on the plane of the celestial meridian, or by computation. When computation is used, solution is made for the meridian angle at which the required negative altitude occurs. The meridian angle expressed in time units is the semiduration in the case of sunrise, sunset, moonrise, and moonset; and the semiduration of the combined sunlight and twilight, or the time from meridian transit at which morning twilight begins or evening twilight ends. For sunrise and sunset the altitude used is (-)50'. Allowance for height of eye can be made by algebraically subtracting (numerically adding) the dip correction from this altitude. The altitude used for twilight is (-)6°, (-)12°, or (-)18° for civil, nautical, or astronomical twilight, respectively. The altitude used for moonrise and moonset is -34' - SD + HP, where SD is semidiameter and HP is horizontal parallax, from the daily pages of the *Nautical Almanac*.

1912. Rising, Setting, And Twilight On A Moving Craft

Instructions to this point relate to a fixed position on the earth. Aboard a moving craft the problem is complicated somewhat by the fact that time of occurrence depends upon position of the craft, which itself depends on the time. At ship speeds, it is generally sufficiently accurate to make an approximate mental solution and use the position of the vessel at this time to make a more accurate solution. If greater accuracy is required, the position at the time indicated in the second solution can be used for a third solution. If desired, this process can be repeated until the same answer is obtained from two consecutive solutions. However, it is generally sufficient to alter the first solution by 1^m for each 15' of longitude that the position of the craft differs from that used in the solution, adding if west of the estimated position, and subtracting if east of it. In applying this rule, use both longitudes to the nearest 15'. The first solution is the **first estimate**; the second solution is the **second estimate**.

CHAPTER 20

SIGHT REDUCTION

BASIC PRINCIPLES

2000. Introduction

Reducing a celestial sight to obtain a line of position consists of six steps:

1. Correcting sextant altitude (hs) to obtain observed altitude (ho).
2. Determining the body's GHA and declination.
3. Selecting an assumed position and finding that position's local hour angle.
4. Computing altitude and azimuth for the assumed position.
5. Comparing computed and observed altitudes.
6. Plotting the line of position.

This chapter concentrates on using the *Nautical Almanac* and *Pub. No. 229, Sight Reduction Tables for Marine Navigation.*

The introduction to each volume of the *Sight Reduction Tables* contains information: (1) discussing use of the publication in a variety of special celestial navigation techniques; (2) discussing interpolation, explaining the double second difference interpolation required in some sight reductions, and providing tables to facilitate the interpolation process; and (3) discussing the publication's use in solving problems of great circle sailings. Prior to using the *Sight Reduction Tables*, carefully read this introductory material.

Celestial navigation involves determining a circular line of position based on an observer's distance from a celestial body's geographic position (GP). Should the observer determine both a body's GP and his distance from the GP, he would have enough information to plot a line of position; he would be somewhere on a circle whose center was the GP and whose radius equaled his distance from that GP. That circle, from all points on which a body's measured altitude would be equal, is a **circle of equal altitude**. There is a direct proportionality between a body's altitude as measured by an observer and the distance of its GP from that observer; the lower the altitude, the farther away the GP. Therefore, when an observer measures a body's altitude he obtains an indirect measure of the distance between himself and the body's GP. Sight reduction is the process of converting that indirect measurement into a line of position.

Sight reduction reduces the problem scale to manageable size. Depending on a body's altitude, its GP could be thousands of miles from the observer's position. The size of a chart required to plot this large distance would be impractical. To eliminate this problem, the navigator does not plot this line of position directly. Indeed, he does not plot the GP at all. Rather, he chooses an **assumed position (AP)** near, but usually not coincident with, his DR position. The navigator chooses the AP's latitude and longitude to correspond to the entering arguments of LHA and latitude used in the *Sight Reduction Tables*. From the *Sight Reduction Tables*, the navigator computes what the body's altitude *would have been* had it been measured from the AP. This yields the **computed altitude** (**h_c**). He then compares this computed value with the **observed altitude** (**h_o**) obtained at his actual position. The difference between the computed and observed altitudes is directly proportional to the distance between the circles of equal altitude for the assumed position and the actual position. The *Sight Reduction Tables* also give the *direction* from the GP to the AP. Having selected the assumed position, calculated the distance between the circles of equal altitude for that AP and his actual position, and determined the direction from the assumed position to the body's GP, the navigator has enough information to plot a line of position (LOP).

To plot an LOP, plot the assumed position on either a chart or a plotting sheet. From the *Sight Reduction Tables*, determine: 1) the altitude of the body for a sight taken at the AP and 2) the direction from the AP to the GP. Then, determine the difference between the body's calculated altitude at this AP and the body's measured altitude. This difference represents the difference in radii between the equal altitude circle passing through the AP and the equal altitude circle passing through the actual position. Plot this difference from the AP either *towards* or *away from* the GP along the axis between the AP and the GP. Finally, draw the circle of equal altitude representing the circle with the body's GP at the center and with a radius equal to the distance between the GP and the navigator's actual position.

One final consideration simplifies the plotting of the equal altitude circle. Recall that the GP is usually thousands of miles away from the navigator's position. The equal altitude circle's radius, therefore, can be extremely large. Since this radius is so large, the navigator can approximate the section close to his position with a straight line drawn perpendicular to the line connecting the AP and the GP. This straight line approximation is good only for sights of relatively low altitudes. The higher the altitude, the shorter the distance between the GP and the actual position, and the

smaller the circle of equal altitude. The shorter this distance, the greater the inaccuracy introduced by this approximation.

2001. Selection Of The Assumed Position (AP)

Use the following arguments when entering the *Sight Reduction Tables* to compute altitude (h_c) and azimuth:

1. Latitude (L).
2. Declination (d or Dec.).
3. Local hour angle (LHA).

Latitude and LHA are functions of the assumed position. Select an AP longitude resulting in a whole degree of LHA and an AP latitude equal to that whole degree of latitude closest to the DR position. Selecting the AP in this manner eliminates interpolation for LHA and latitude in the *Sight Reduction Tables*.

Reducing the sight using a computer or calculator simplifies this AP selection process. Simply choose any convenient position such as the vessel's DR position as the assumed position. Enter the information required by the specific celestial program in use. Using a calculator reduces the math and interpolation errors inherent in using the *Sight Reduction* tables. Enter the required calculator data carefully.

2002. Comparison Of Computed And Observed Altitudes

The difference between the computed altitude (h_c) and the observed altitude (h_o) is the **altitude intercept** (a).

The altitude intercept is the difference in the length of the radii of the circles of equal altitude passing through the AP and the observers actual position. The position having the greater altitude is on the circle of smaller radius and is closer to the observed body's GP. In Figure 2003, the AP is shown on the inner circle. Therefore, h_c is greater than h_o.

Express the altitude intercept in nautical miles and label it T or A to indicate whether the line of position is toward or away from the GP, as measured from the AP.

A useful aid in remembering the relation between h_o, h_c, and the altitude intercept is: $\underline{H}_o$ $\underline{M}_o$ $\underline{T}_o$ for H_o <u>More</u> <u>Toward</u>. Another is C-G-A: <u>C</u>omputed <u>G</u>reater <u>A</u>way, remembered as <u>C</u>oast <u>G</u>uard <u>A</u>cademy. In other words, if h_o is greater than h_c, the line of position intersects a point measured from the AP towards the GP a distance equal to the altitude intercept. Draw the LOP through this intersection point perpendicular to the axis between the AP and GP.

2003. Plotting The Line Of Position

Plot the line of position as shown in Figure 2003. Plot the AP first; then plot the azimuth line from the AP toward or away from the GP. Then, measure the altitude intercept along this line. At the point on the azimuth line equal to the intercept distance, draw a line perpendicular to the azimuth line. This perpendicular represents that section of the circle of equal altitude passing through the navigator's actual position. This is the line of position.

A navigator often takes sights of more than one celestial body when determining a celestial fix. After plotting the lines of position from these several sights, advance the resulting LOP's along the track to the time of the last sight and label the resulting fix with the time of this last sight.

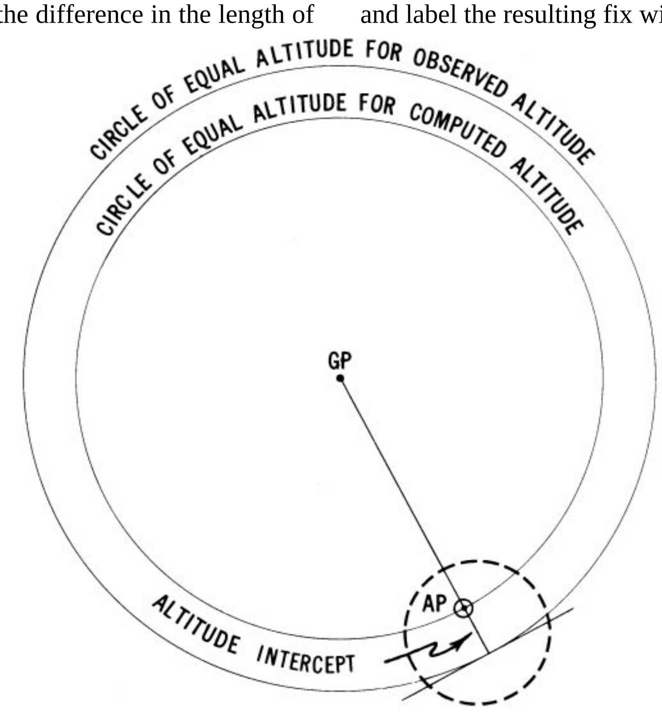


Figure 2003. The basis for the line of position from a celestial observation.

2004. Recommended Sight Reduction Procedure

Just as it is important to understand the theory of sight reduction, it is also important to develop a working procedure to reduce celestial sights accurately. Sight reduction involves several consecutive steps, the accuracy of each completely dependent on the accuracy of the steps that went before. Sight reduction tables have, for the most part, reduced the mathematics involved to simple addition and subtraction. However, careless errors will render even the most skillfully measured sights inaccurate. The navigator must work methodically to reduce these careless errors.

Naval navigators will most likely use OPNAV 3530, U.S. Navy Navigation Workbook, which contains pre-formatted pages with “strip forms” to guide the navigator through sight reduction. A variety of commercially-produced forms are also available. Pick a form and learn its method *thoroughly*. With familiarity will come increasing understanding.

Figure 2004 represents a functional and complete worksheet designed to ensure a methodical approach to any sight reduction problem. The recommended procedure discussed below is not the only one available; however, the navigator who uses it can be assured that he has considered *every* correction required to obtain an accurate fix.

SECTION ONE consists of two parts: (1) Correcting sextant altitude to obtain apparent altitude; and (2) Correcting the apparent altitude to obtain the observed altitude.

Body: Enter the name of the body whose altitude you have measured. If using the sun or the moon, indicate which limb was measured.

Index Correction: This is determined by the characteristics of the individual sextant used. Chapter 16 discusses determining its magnitude and algebraic sign.

Dip: The dip correction is a function of the height of eye of the observer. It is always negative; its magnitude is determined from the Dip Table on the inside front covert of the *Nautical Almanac*.

Sum: Enter the algebraic sum of the dip correction and the index correction.

Sextant Altitude: Enter the altitude of the body measured by the sextant.

Apparent Altitude: Apply the sum correction determined above to the measured altitude and enter the result as the apparent altitude.

Altitude Correction: Every observation requires an altitude correction. This correction is a function of the apparent altitude of the body. The *Almanac* contains tables for determining these corrections. For the sun, planets, and stars, these tables are located on the inside front cover and facing page. For the moon, these tables are located on the back inside cover and preceding page.

Mars or Venus Additional Correction: As the name implies, this correction is applied to sights of Mars and Venus. The correction is a function of the planet measured, the time of year, and the apparent altitude. The inside front cover of the *Almanac* lists these corrections.

Additional Correction: Enter this additional correction from Table A 4 located at the front of the *Almanac* when obtaining a sight under non-standard atmospheric temperature and pressure conditions. This correction is a function of atmospheric pressure, temperature, and apparent altitude.

Horizontal Parallax Correction: This correction is unique to reducing moon sights. Obtain the H.P. correction value from the daily pages of the *Almanac*. Enter the H.P correction table at the back of the *Almanac* with this value. The H.P correction is a function of the limb of the moon used (upper or lower), the apparent altitude, and the H.P. correction factor. The H.P. correction is always added to the apparent altitude.

Moon Upper Limb Correction: Enter -30' for this correction if the sight was of the upper limb of the moon.

Correction to Apparent Altitude: Sum the altitude correction, the Mars or Venus additional correction, the additional correction, the horizontal parallax correction, and the moon’s upper limb correction. Be careful to determine and carry the algebraic sign of the corrections and their sum correctly. Enter this sum as the correction to the apparent altitude.

Observed Altitude: Apply the Correction to Apparent Altitude algebraically to the apparent altitude. The result is the observed altitude.

SECTION TWO determines the Greenwich Mean Time (GMT) and GMT date of the sight.

Date: Enter the local time zone date of the sight.

DR Latitude: Enter the dead reckoning latitude of the vessel.

DR Longitude: Enter the dead reckoning longitude of the vessel.

Observation Time: Enter the local time of the sight as recorded on the ship’s chronometer or other timepiece.

Watch Error: Enter a correction for any known watch error.

Zone Time: Correct the observation time with watch error to determine zone time.

Zone Description: Enter the zone description of the time zone indicated by the DR longitude. If the longitude is west of the Greenwich Meridian, the zone description is positive. Conversely, if the longitude is east of the Greenwich Meridian, the zone description is negative. The zone description represents the correction necessary to convert local time to Greenwich Mean Time.

Greenwich Mean Time: Add to the zone description the zone time to determine Greenwich Mean Time.

Date: Carefully evaluate the time correction applied above and determine if the correction has changed the date. Enter the GMT date.

SECTION THREE determines two of the three arguments required to enter the *Sight Reduction Tables*: Local Hour Angle (LHA) and Declination. This section employs the principle that a celestial body’s LHA is the algebraic sum of its Greenwich Hour Angle (GHA) and the observer’s lon-

SECTION ONE: OBSERVED ALTITUDE

Body	....	....
Index Correction	....	....
Dip (height of eye)	....	....
Sum	....	....
Sextant Altitude (h_s)	....	....
Apparent Altitude (h_a)	....	....
Altitude Correction	....	....
Mars or Venus Additional Correction	....	....
Additional Correction	....	....
Horizontal Parallax Correction	....	....
Moon Upper Limb Correction	....	....
Correction to Apparent Altitude (h_a)	....	....
Observed Altitude (h_o)	....	....

SECTION TWO: GMT TIME AND DATE

Date	....	....
DR Latitude	....	....
DR Longitude	....	....
Observation Time	....	....
Watch Error	....	....
Zone Time	....	....
Zone Description	....	....
Greenwich Mean Time	....	....
Date GMT	....	....

SECTION THREE: LOCAL HOUR ANGLE AND DECLINATION

Tabulated GHA and *v* Correction Factor	....	....
GHA Increment	....	....
Sidereal Hour Angle (SHA) or *v* Correction	....	....
GHA	....	....
+ or - 360° if needed	....	....
Assumed Longitude (-W, +E)	....	....
Local Hour Angle (LHA)	....	....
Tabulated Declination and *d* Correction Factor	....	....
d Correction	....	....
True Declination	....	....
Assumed Latitude	....	....

SECTION FOUR: ALTITUDE INTERCEPT AND AZIMUTH

Declination Increment and *d* Interpolation Factor	....	....
Computed Altitude (Tabulated)	....	....
Double Second Difference Correction	....	....
Total Correction	....	....
Computed Altitude (h_c)	....	....
Observed Altitude (h_o)	....	....
Altitude Intercept	....	....
Azimuth Angle	....	....
True Azimuth	....	....

Figure 2004. Complete sight reduction form.

gitude. Therefore, the basic method employed in this section is: (1) Determine the body's GHA; (2) Determine an assumed longitude; (3) Algebraically combine the two quantities, remembering to subtract a western assumed longitude from GHA and to add an eastern longitude to GHA; and (4) Extract the declination of the body from the appropriate Almanac table, correcting the tabular value if required.

(1) Tabulated GHA and (2) *v* Correction Factor:

(1) For the sun, the moon, or a planet, extract the value for the whole hour of GHA corresponding to the sight. For example, if the sight was obtained at 13-50-45 GMT, extract the GHA value for 1300. For a star sight reduction, extract the value of the GHA of Aries (GHA ♈), again using the value corresponding to the whole hour of the time of the sight.

(2) For a planet or moon sight reduction, enter the *v* correction value. This quantity is not applicable to a sun or star sight. The *v* correction for a planet sight is found at the bottom of the column for each particular planet. The *v* correction factor for the moon is located directly beside the tabulated hourly GHA values. The *v* correction factor for the moon is always positive. If a planet's *v* correction factor is listed without sign, it is positive. If listed with a negative sign, the planet's *v* correction factor is negative. This *v* correction factor is not the magnitude of the *v* correction; it is used later to enter the Increments and Correction table to determine the magnitude of the correction.

GHA Increment: The GHA increment serves as an interpolation factor, correcting for the time that the sight differed from the whole hour. For example, in the sight at 13-50-45 discussed above, this increment correction accounts for the 50 minutes and 45 seconds after the whole hour at which the sight was taken. Obtain this correction value from the Increments and Corrections tables in the *Almanac*. The entering arguments for these tables are the minutes and seconds after the hour at which the sight was taken and the body sighted. Extract the proper correction from the applicable table and enter the correction here.

Sidereal Hour Angle or *v* Correction: If reducing a star sight, enter the star's Sidereal Hour Angle (SHA). The SHA is found in the star column of the daily pages of the *Almanac*. The SHA combined with the GHA of Aries results in the star's GHA. The SHA entry is applicable only to a star. If reducing a planet or moon sight, obtain the *v* correction from the Increments and Corrections Table. The correction is a function of only the *v* correction factor; its magnitude is the same for both the moon and the planets.

GHA: A star's GHA equals the sum of the Tabulated GHA of Aries, the GHA Increment, and the star's SHA. The sun's GHA equals the sum of the Tabulated GHA and the GHA Increment. The GHA of the moon or a planet equals the sum of the Tabulated GHA, the GHA Increment, and the *v* correction.

+ or – 360° (if needed): Since the LHA will be determined from subtracting or adding the assumed longitude to the GHA, adjust the GHA by 360° if needed to facilitate the addition or subtraction.

Assumed Longitude: If the vessel is west of the prime meridian, the assumed longitude will be subtracted from the GHA to determine LHA. If the vessel is east of the prime meridian, the assumed longitude will be added to the GHA to determine the LHA. Select the assumed longitude to meet the following two criteria: (1) When added or subtracted (as applicable) to the GHA determined above, a whole degree of LHA will result; and (2) It is the longitude closest to that DR longitude that meets criterion (1) above.

Local Hour Angle (LHA): Combine the body's GHA with the assumed longitude as discussed above to determine the body's LHA.

(1) Tabulated Declination and *d* Correction factor: (1) Obtain the tabulated declination for the sun, the moon, the stars, or the planets from the daily pages of the *Almanac*. The declination values for the stars are given for the entire three day period covered by the daily page of the *Almanac*. The values for the sun, moon, and planets are listed in hourly increments. For these bodies, enter the declination value for the whole hour of the sight. For example, if the sight is at 12-58-40, enter the tabulated declination for 1200. (2) There is no *d* correction factor for a star sight. There are *d* correction factors for sun, moon, and planet sights. Similar to the v correction factor discussed above, the *d* correction factor does not equal the magnitude of the *d* correction; it provides the argument to enter the Increments and Corrections tables in the *Almanac*. The sign of the *d* correction factor, which determines the sign of the *d* correction, is determined by the trend of declination values, *not* the trend of *d* values. The *d* correction factor is simply an interpolation factor; therefore, to determine its sign, look at the declination values for the hours that frame the time of the sight. For example, suppose the sight was taken on a certain date at 12-30-00. Compare the declination value for 1200 and 1300 and determine if the declination has increased or decreased. If it has increased, the *d* correction factor is positive. If it has decreased, the *d* correction factor is negative.

***d* correction:** Enter the Increments and Corrections table with the *d* correction factor discussed above. Extract the proper correction, being careful to retain the proper sign.

True Declination: Combine the tabulated declination and the *d* correction to obtain the true declination.

Assumed Latitude: Choose as the assumed latitude that whole value of latitude closest to the vessel's DR latitude. If the assumed latitude and declination are both north or both south, label the assumed latitude *same*. If one is north and the other is south, label the assumed latitude *contrary*.

SECTION FOUR uses the arguments of assumed latitude, LHA, and declination determined in Section Three to enter the *Sight Reduction Tables* to determine azimuth and computed altitude. Then, Section Four compares computed and observed altitudes to calculate the altitude intercept. The navigator then has enough information to plot the line of position.

(1) Declination Increment and (2) *d* Interpolation Factor: Note that two of the three arguments used to enter the *Sight Reduction Tables*, LHA and latitude, are whole degree values. Section Three does not determine the third argument, declination, as a whole degree. Therefore, the navigator must interpolate in the *Sight Reduction Tables* for declination, given whole degrees of LHA and latitude. The first steps of Section Four involve this interpolation for declination. Since declination values are tabulated every whole degree in the *Sight Reduction Tables*, the declination increment is the minutes and tenths of the true declination. For example, if the true declination is 13° 15.6', then the declination increment is 15.6'. (2) The *Sight Reduction Tables* also list a *d* Interpolation Factor. This is the magnitude of the difference between the two successive tabulated values for declination that frame the true declination. Therefore, for the hypothetical declination listed above, the tabulated *d* interpolation factor listed in the table would be the difference between declination values given for 13° and 14°. If the declination increases between these two values, *d* is positive. If the declination decreases between these two values, *d* is negative.

Computed Altitude (Tabulated): Enter the *Sight Reduction Tables* with the following arguments: (1) LHA from Section Three; (2) assumed latitude from Section Three; (3) the whole degree value of the true declination. For example, if the true declination were 13° 15.6', then enter the *Sight Reduction Tables* with 13° as the value for declination. Record the tabulated computed altitude.

Double Second Difference Correction: Use this correction when linear interpolation of declination for computed altitude is not sufficiently accurate due to the non linear change in the computed altitude as a function of declination. The need for double second difference interpolation is indicated by the *d* interpolation factor appearing in italic type followed by a small dot. When this procedure must be employed, refer to detailed instructions in the *Sight Reduction Tables* introduction.

Total Correction: The total correction is the sum of the double second difference (if required) and the interpolation corrections. Calculate the interpolation correction by dividing the declination increment by 60' and multiply the resulting quotient by the *d* interpolation factor.

Computed Altitude (h_c): Apply the total correction, being careful to carry the correct sign, to the tabulated computed altitude. This yields the computed altitude.

Observed Altitude (h_o): Enter the observed altitude from Section One.

Altitude Intercept: Compare h_c and h_o. Subtract the smaller from the larger. The resulting difference is the magnitude of the altitude intercept. If h_o is greater than h_c, then label the altitude intercept *toward*. If h_c is greater than h_o, then label the altitude intercept *away*.

Azimuth Angle: Obtain the azimuth angle (Z) from the *Sight Reduction Tables*, using the same arguments which determined tabulated computed altitude. Visual interpolation is sufficiently accurate.

True Azimuth: Calculate the true azimuth (Z_n) from the azimuth angle (Z) as follows:

a) If in northern latitudes:

$$\text{LHA} > 180°\text{, then } Z_n = Z$$
$$\text{LHA} < 180°\text{, then } Z_n = 360° - Z$$

b) If in southern latitudes:

$$\text{LHA} > 180°\text{, then } Z_n = 180° - Z$$
$$\text{LHA} < 180°\text{, then } Z_n = 180° + Z$$

SIGHT REDUCTION

The section above discussed the basic theory of sight reduction and proposed a method to be followed when reducing sights. This section puts that method into practice in reducing sights of a star, the sun, the moon, and planets.

2005. Reducing Star Sights To A Fix

On May 16, 1995, at the times indicated, the navigator takes and records the following sights:

Star	Sextant Altitude	Zone Time
Kochab	47° 19.1'	20-07-43
Spica	32° 34.8'	20-11-26

Height of eye is 48 feet and index correction (IC) is +2.1'. The DR latitude for both sights is 39° N. The DR longitude for the Spica sight is 157° 10'W. The DR longitude for the Kochab sight is 157° 08.0'W. Determine the intercept and azimuth for both sights. See Figure 2005.

First, convert the sextant altitudes to observed altitudes. Reduce the Spica sight first:

Body	Spica
Index Correction	+2.1'
Dip (height 48 ft)	-6.7'
Sum	-4.6'
Sextant Altitude (h_s)	32° 34.8'
Apparent Altitude (h_a)	32° 30.2'
Altitude Correction	-1.5'
Additional Correction	0
Horizontal Parallax	0
Correction to h_a	-1.5'
Observed Altitude (h_o)	32° 28.7'

Determine the sum of the index correction and the dip

correction. Go to the inside front cover of the Nautical Almanac to the table entitled DIP. This table lists dip corrections as a function of height of eye measured in either feet or meters. In the above problem, the observer's height of eye is 48 feet. The heights of eye are tabulated in intervals, with the correction corresponding to each interval listed between the interval's endpoints. In this case, 48 feet lies between the tabulated 46.9 to 48.4 feet interval; the corresponding correction for this interval is -6.7'. Add the IC and the dip correction, being careful to carry the correct sign. The sum of the corrections here is -4.6'. Apply this correction to the sextant altitude to obtain the apparent altitude (h_a).

Next, apply the altitude correction. Find the altitude correction table on the inside front cover of the *Nautical Almanac* next to the dip table. The altitude correction varies as a function of both the type of body sighted (sun, star, or planet) and the body's apparent altitude. For the problem above, enter the star altitude correction table. Again, the correction is given within an altitude interval; h_a in this case was 32° 30.2'. This value lies between the tabulated endpoints 32° 00.0' and 33° 45.0'. The correction corresponding to this interval is -1.5'. Applying this correction to h_a yields an observed altitude of 32° 28.7'.

Having calculated the observed altitude, determine the time and date of the sight in Greenwich Mean Time:

Date	16 May 1995
DR Latitude	39° N
DR Longitude	157° 10' W
Observation Time	20-11-26
Watch Error	0
Zone Time	20-11-26
Zone Description	+10
GMT	06-11-26
GMT Date	17 May 1995

Record the observation time and then apply any watch error to determine zone time. Then, use the DR longitude at the time of the sight to determine time zone description. In this case, the DR longitude indicates a zone description of +10 hours. Add the zone description to the zone time to obtain GMT. It is important to carry the correct date when applying this correction. In this case, the +10 correction made it 06-11-26 GMT on May <u>17</u>, when the date in the local time zone was May <u>16</u>.

After calculating both the observed altitude and the GMT time, enter the daily pages of the *Nautical Almanac* to calculate the star's Greenwich Hour Angle (GHA) and declination.

Tab GHA ♈	324° 28.4'
GHA Increment	2° 52.0'
SHA	158° 45.3'
GHA	486° 05.7'
+/- 360°	not required
Assumed Longitude	157° 05.7'
LHA	329°
Tabulated Dec/*d*	S 11° 08.4'/n.a.
d Correction	—
True Declination	S 11° 08.4'
Assumed Latitude	N 39° contrary

First, record the GHA of Aries from the May 17, 1995 daily page: 324° 28.4'.

Next, determine the incremental addition for the minutes and seconds after 0600 from the Increments and Corrections table in the back of the *Nautical Almanac*. The increment for 11 minutes and 26 seconds is 2° 52'.

Then, calculate the GHA of the star. Remember:

GHA (star) = GHA ♈ + SHA (star)

The *Nautical Almanac* lists the SHA of selected stars on each daily page. The SHA of Spica on May 17, 1995:158° 45.3'.

The *Sight Reduction Tables*' entering arguments are whole degrees of LHA and assumed latitude. Remember that LHA = GHA - west longitude or GHA + east longitude. Since in this example the vessel is in west longitude, subtract its assumed longitude from the GHA of the body to obtain the LHA. Assume a longitude meeting the criteria listed in section 2004.

From those criteria, the assumed longitude must end in 05.7 minutes so that, when subtracted from the calculated GHA, a whole degree of LHA will result. Since the DR longitude was 157° 10.0', then the assumed longitude ending in 05.7' closest to the DR longitude is 157° 05.7'. Subtracting this assumed longitude from the calculated GHA of the star yields an LHA of 329°.

The next value of concern is the star's true declination. This value is found on the May 17th daily page next to the star's SHA. Spica's declination is S 11° 08.4'. There is no d correction for a star sight, so the star's true declination equals its tabulated declination. The assumed latitude is determined from the whole degree of latitude closest to the DR latitude at the time of the sight. In this case, the assumed latitude is N 39°. It is marked "contrary" because the DR latitude is north while the star's declination is south.

The following information is known: (1) the assumed position's LHA (329°) and assumed latitude (39°N contrary name); and (2) the body's declination (S11° 08.4').

Find the page in the *Sight Reduction Table* corresponding to an LHA of 329° and an assumed latitude of N 39°, with latitude contrary to declination. Enter this table with the body's whole degree of declination. In this case, the body's whole degree of declination is 11°. This declination corresponds to a tabulated altitude of 32° 15.9'. This value is for a declination of 11°; the true declination is 11° 08.4'. Therefore, interpolate to determine the correction to add to the tabulated altitude to obtain the computed altitude.

The difference between the tabulated altitudes for 11° and 12° is given in the *Sight Reduction Tables* as the value

d; in this case, d = -53.0. Express as a ratio the declination increment (in this case, 8.4') and the total interval between the tabulated declination values (in this case, 60') to obtain the percentage of the distance between the tabulated declination values represented by the declination increment. Next, multiply that percentage by the increment between the two values for computed altitude. In this case:

$$\frac{8.4}{60} \times (-53.0) = -7.4$$

Subtract 7.4' from the tabulated altitude to obtain the final computed altitude: H_c = 32° 08.5'.

Dec Inc / + or - d	8.4' / -53.0
h_c (tabulated)	32° 15.9'
Correction (+ or -)	-7.4'
h_c (computed)	32° 08.5'

It will be valuable here to review exactly what h_o and h_c represent. Recall the methodology of the altitude-intercept method. The navigator first measures and corrects an altitude for a celestial body. This corrected altitude, h_o, corresponds to a circle of equal altitude passing through the navigator's actual position whose center is the geographic position (GP) of the body. The navigator then determines an assumed position (AP) near, but not coincident with, his actual position; he then calculates an altitude for an observer at that assumed position (AP).The circle of equal altitude passing through this assumed position is concentric with the circle of equal altitude passing through the navigator's actual position. The difference between the body's altitude at the assumed position (h_c) and the body's observed altitude (h_o) is equal to the differences in radii length of the two corresponding circles of equal altitude. In the above problem, therefore, the navigator knows that the equal altitude circle passing through his actual position is:

$$\begin{aligned} h_o &= 32°28.7' \\ -h_c &= \underline{32°08.5'} \\ &\quad\; 20.2\text{ NM} \end{aligned}$$

away from the equal altitude circle passing through his assumed position. Since h_o is greater than h_c, the navigator knows that the radius of the equal altitude circle passing through his actual position is less than the radius of the equal altitude circle passing through the assumed position. The only remaining question is: in what direction from the assumed and actual position is the body's geographic position. The *Sight Reduction Tables* also provide this final piece of information. This is the value for Z tabulated with the h_c and d values discussed above. In this case, enter the *Sight Reduction Tables* as before, with LHA, assumed latitude, and declination. Visual interpolation is sufficient. Extract the value Z = 143.3°. The relation between Z and Z_n, the true azimuth, is as follows:

In northern latitudes:

$$\text{LHA} > 180°, \text{ then } Z_n = Z$$
$$\text{LHA} < 180°, \text{ then } Z_n = 360° - Z$$

In southern latitudes:

$$\text{LHA} > 180°, \text{ then } Z_n = 180° - Z$$
$$\text{LHA} < 180°, \text{ then } Z_n = 180° + Z$$

In this case, LHA > 180° and the vessel is in northern latitude. Therefore, Z_n = Z = 143.3°T. The navigator now has enough information to plot a line of position.

The values for the reduction of the Kochab sight follow:

Body	Kochab
Index Correction	+2.1'
Dip Correction	-6.7'
Sum	-4.6'
h_s	47° 19.1'
h_a	47° 14.5'
Altitude Correction	-.9'
Additional Correction	not applicable
Horizontal Parallax	not applicable
Correction to h_a	-9'
h_o	47° 13.6'
Date	16 May 1995
DR latitude	39°N
DR longitude	157° 08.0' W
Observation Time	20-07-43
Watch Error	0
Zone Time	20-07-43
Zone Description	+10
GMT	06-07-43
GMT Date	17 May 1995
Tab GHA ♈	324° 28.4'
GHA Increment	1° 56.1'
SHA	137° 18.5'
GHA	463° 43.0'
+/- 360°	not applicable
Assumed Longitude	156° 43.0'
LHA	307°
Tab Dec / *d*	N74° 10.6' / n.a.
d Correction	not applicable
True Declination	N74° 10.6'
Assumed Latitude	39°N (same)
Dec Inc / + or - d	10.6' / -24.8
h_c	47° 12.6'
Total Correction	-4.2'

1995 MAY 16, 17, 18 (TUES., WED., THURS.)

UT (GMT)	ARIES	VENUS −3.9		MARS +0.7		JUPITER −2.5		SATURN +1.3		STARS		
	G.H.A.	G.H.A.	Dec.	G.H.A.	Dec.	G.H.A.	Dec.	G.H.A.	Dec.	Name	S.H.A.	Dec.
d h	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′		° ′	° ′
16 00	233 14.4	205 51.6	N 9 30.5	84 34.3	N14 31.2	342 02.6	S21 28.7	239 13.9	S 4 40.8	Acamar	315 29.1	S40 19.4
01	248 16.9	220 51.2	31.6	99 35.8	30.8	357 05.3	28.7	254 16.2	40.7	Achernar	335 37.4	S57 15.5
02	263 19.4	235 50.8	32.7	114 37.3	30.3	12 08.1	28.7	269 18.5	40.6	Acrux	173 24.0	S63 04.7
03	278 21.8	250 50.4	· · 33.8	129 38.8	· · 29.9	27 10.9	· · 28.6	284 20.7	· · 40.6	Adhara	255 23.5	S28 58.3
04	293 24.3	265 50.0	34.9	144 40.3	29.5	42 13.7	28.6	299 23.0	40.5	Aldebaran	291 05.3	N16 29.9
05	308 26.8	280 49.6	36.0	159 41.7	29.1	57 16.4	28.5	314 25.3	40.4			
06	323 29.2	295 49.2	N 9 37.1	174 43.2	N14 28.7	72 19.2	S21 28.5	329 27.6	S 4 40.4	Alioth	166 32.3	N55 59.2
07	338 31.7	310 48.8	38.2	189 44.7	28.3	87 22.0	28.5	344 29.9	40.3	Alkaid	153 09.2	N49 20.3
T 08	353 34.2	325 48.4	39.2	204 46.2	27.9	102 24.7	28.4	359 32.1	40.2	Al Na'ir	28 00.8	S46 58.7
U 09	8 36.6	340 48.0	· · 40.3	219 47.7	· · 27.5	117 27.5	· · 28.4	14 34.4	· · 40.2	Alnilam	276 00.5	S 1 12.5
E 10	23 39.1	355 47.6	41.4	234 49.2	27.1	132 30.3	28.4	29 36.7	40.1	Alphard	218 09.5	S 8 38.6
S 11	38 41.5	10 47.1	42.5	249 50.6	26.6	147 33.1	28.3	44 39.0	40.0			
D 12	53 44.0	25 46.7	N 9 43.6	264 52.1	N14 26.2	162 35.8	S21 28.3	59 41.3	S 4 40.0	Alphecca	126 22.2	N26 43.8
A 13	68 46.5	40 46.3	44.7	279 53.6	25.8	177 38.6	28.3	74 43.6	39.9	Alpheratz	357 57.8	N29 03.8
Y 14	83 48.9	55 45.9	45.8	294 55.1	25.4	192 41.4	28.2	89 45.8	39.8	Altair	62 21.3	N 8 51.4
15	98 51.4	70 45.5	· · 46.9	309 56.6	· · 25.0	207 44.2	· · 28.2	104 48.1	· · 39.8	Ankaa	353 29.4	S42 19.7
16	113 53.9	85 45.1	47.9	324 58.0	24.6	222 46.9	28.2	119 50.4	39.7	Antares	112 42.6	S26 25.3
17	128 56.3	100 44.7	49.0	339 59.5	24.2	237 49.7	28.1	134 52.7	39.6			
18	143 58.8	115 44.3	N 9 50.1	355 01.0	N14 23.8	252 52.5	S21 28.1	149 55.0	S 4 39.6	Arcturus	146 07.8	N19 12.4
19	159 01.3	130 43.9	51.2	10 02.5	23.3	267 55.3	28.1	164 57.3	39.5	Atria	107 56.1	S69 01.0
20	174 03.7	145 43.5	52.3	25 03.9	22.9	282 58.0	28.0	179 59.5	39.4	Avior	234 23.8	S59 30.1
21	189 06.2	160 43.1	· · 53.4	40 05.4	· · 22.5	298 00.8	· · 28.0	195 01.8	· · 39.4	Bellatrix	278 46.9	N 6 20.6
22	204 08.7	175 42.7	54.5	55 06.9	22.1	313 03.6	28.0	210 04.1	39.3	Betelgeuse	271 16.3	N 7 24.2
23	219 11.1	190 42.3	55.5	70 08.4	21.7	328 06.3	27.9	225 06.4	39.2			
17 00	234 13.6	205 41.9	N 9 56.6	85 09.8	N14 21.3	343 09.1	S21 27.9	240 08.7	S 4 39.1	Canopus	264 02.6	S52 41.9
01	249 16.0	220 41.5	57.7	100 11.3	20.9	358 11.9	27.8	255 11.0	39.1	Capella	280 55.0	N45 59.5
02	264 18.5	235 41.1	58.8	115 12.8	20.5	13 14.7	27.8	270 13.2	39.0	Deneb	49 40.6	N45 15.7
03	279 21.0	250 40.7	9 59.9	130 14.3	· · 20.0	28 17.4	· · 27.8	285 15.5	· · 38.9	Denebola	182 47.4	N14 35.8
04	294 23.4	265 40.3	10 01.0	145 15.7	19.6	43 20.2	27.7	300 17.8	38.9	Diphda	349 09.8	S18 00.7
05	309 25.9	280 39.8	02.0	160 17.2	19.2	58 23.0	27.7	315 20.1	38.8			
06	324 28.4	295 39.4	N10 03.1	175 18.7	N14 18.8	73 25.8	S21 27.7	330 22.4	S 4 38.7	Dubhe	194 08.2	N61 46.7
W 07	339 30.8	310 39.0	04.2	190 20.2	18.4	88 28.6	27.6	345 24.7	38.7	Elnath	278 30.2	N28 36.1
E 08	354 33.3	325 38.6	05.3	205 21.6	18.0	103 31.3	27.6	0 26.9	38.6	Eltanin	90 52.0	N51 29.3
D 09	9 35.8	340 38.2	· · 06.4	220 23.1	· · 17.5	118 34.1	· · 27.6	15 29.2	· · 38.5	Enif	34 00.5	N 9 51.2
N 10	24 38.2	355 37.8	07.4	235 24.6	17.1	133 36.9	27.5	30 31.5	38.5	Fomalhaut	15 39.1	S29 38.6
E 11	39 40.7	10 37.4	08.5	250 26.0	16.7	148 39.7	27.5	45 33.8	38.4			
S 12	54 43.1	25 37.0	N10 09.6	265 27.5	N14 16.3	163 42.4	S21 27.5	60 36.1	S 4 38.3	Gacrux	172 15.6	S57 05.5
D 13	69 45.6	40 36.6	10.7	280 29.0	15.9	178 45.2	27.4	75 38.4	38.3	Gienah	176 06.1	S17 31.2
A 14	84 48.1	55 36.2	11.8	295 30.5	15.5	193 48.0	27.4	90 40.7	38.2	Hadar	149 06.6	S60 21.2
Y 15	99 50.5	70 35.7	· · 12.8	310 31.9	· · 15.0	208 50.8	· · 27.4	105 42.9	· · 38.1	Hamal	328 16.4	N23 26.3
16	114 53.0	85 35.3	13.9	325 33.4	14.6	223 53.5	27.3	120 45.2	38.1	Kaus Aust.	84 01.5	S34 23.0
17	129 55.5	100 34.9	15.0	340 34.9	14.2	238 56.3	27.3	135 47.5	38.0			
18	144 57.9	115 34.5	N10 16.1	355 36.3	N14 13.8	253 59.1	S21 27.2	150 49.8	S 4 37.9	Kochab	137 18.5	N74 10.6
19	160 00.4	130 34.1	17.2	10 37.8	13.4	269 01.9	27.2	165 52.1	37.9	Markab	13 52.0	N15 10.8
20	175 02.9	145 33.7	18.2	25 39.3	13.0	284 04.6	27.2	180 54.4	37.8	Menkar	314 29.6	N 4 04.2
21	190 05.3	160 33.3	· · 19.3	40 40.7	· · 12.5	299 07.4	· · 27.1	195 56.7	· · 37.7	Menkent	148 23.3	S36 21.0
22	205 07.8	175 32.8	20.4	55 42.2	12.1	314 10.2	27.1	210 58.9	37.7	Miaplacidus	221 42.6	S69 42.4
23	220 10.3	190 32.4	21.5	70 43.7	11.7	329 13.0	27.1	226 01.2	37.6			
18 00	235 12.7	205 32.0	N10 22.5	85 45.1	N14 11.3	344 15.8	S21 27.0	241 03.5	S 4 37.5	Mirfak	309 00.4	N49 50.6
01	250 15.2	220 31.6	23.6	100 46.6	10.9	359 18.5	27.0	256 05.8	37.5	Nunki	76 14.9	S26 18.0
02	265 17.6	235 31.2	24.7	115 48.1	10.5	14 21.3	27.0	271 08.1	37.4	Peacock	53 40.4	S56 44.7
03	280 20.1	250 30.8	· · 25.8	130 49.5	· · 10.0	29 24.1	· · 26.9	286 10.4	· · 37.3	Pollux	243 44.6	N28 02.2
04	295 22.6	265 30.4	26.8	145 51.0	09.6	44 26.9	26.9	301 12.7	37.3	Procyon	245 14.1	N 5 14.0
05	310 25.0	280 29.9	27.9	160 52.5	09.2	59 29.6	26.9	316 15.0	37.2			
06	325 27.5	295 29.5	N10 29.0	175 53.9	N14 08.8	74 32.4	S21 26.8	331 17.2	S 4 37.1	Rasalhague	96 18.8	N12 33.8
07	340 30.0	310 29.1	30.0	190 55.4	08.4	89 35.2	26.8	346 19.5	37.1	Regulus	207 58.0	N11 59.3
T 08	355 32.4	325 28.7	31.1	205 56.9	07.9	104 38.0	26.8	1 21.8	37.0	Rigel	281 25.5	S 8 12.6
H 09	10 34.9	340 28.3	· · 32.2	220 58.3	· · 07.5	119 40.8	· · 26.7	16 24.1	· · 36.9	Rigil Kent.	140 09.6	S60 49.0
U 10	25 37.4	355 27.9	33.3	235 59.8	07.1	134 43.5	26.7	31 26.4	36.9	Sabik	102 27.8	S15 43.1
R 11	40 39.8	10 27.4	34.3	251 01.2	06.7	149 46.3	26.6	46 28.7	36.8			
S 12	55 42.3	25 27.0	N10 35.4	266 02.7	N14 06.3	164 49.1	S21 26.6	61 31.0	S 4 36.8	Schedar	349 56.4	N56 30.5
D 13	70 44.8	40 26.6	36.5	281 04.2	05.8	179 51.9	26.6	76 33.3	36.7	Shaula	96 40.0	S37 05.9
A 14	85 47.2	55 26.2	37.5	296 05.6	05.4	194 54.7	26.5	91 35.6	36.6	Sirius	258 45.9	S16 42.8
Y 15	100 49.7	70 25.8	· · 38.6	311 07.1	· · 05.0	209 57.4	· · 26.5	106 37.8	· · 36.6	Spica	158 45.3	S11 08.4
16	115 52.1	85 25.3	39.7	326 08.6	04.6	225 00.2	26.5	121 40.1	36.5	Suhail	223 02.5	S43 25.2
17	130 54.6	100 24.9	40.7	341 10.0	04.2	240 03.0	26.4	136 42.4	36.4			
18	145 57.1	115 24.5	N10 41.8	356 11.5	N14 03.7	255 05.8	S21 26.4	151 44.7	S 4 36.4	Vega	80 47.8	N38 46.7
19	160 59.5	130 24.1	42.9	11 12.9	03.3	270 08.6	26.4	166 47.0	36.3	Zuben'ubi	137 20.2	S16 01.4
20	176 02.0	145 23.6	44.0	26 14.4	02.9	285 11.3	26.3	181 49.3	36.2			
21	191 04.5	160 23.2	· · 45.0	41 15.9	· · 02.5	300 14.1	· · 26.3	196 51.6	· · 36.2		S.H.A. ° ′	Mer. Pass. h m
22	206 06.9	175 22.8	46.1	56 17.3	02.0	315 16.9	26.2	211 53.9	36.1	Venus	331 28.3	10 17
23	221 09.4	190 22.4	47.2	71 18.8	01.6	330 19.7	26.2	226 56.2	36.0	Mars	210 56.3	18 18
Mer. Pass.	h m 8 21.7	v −0.4	d 1.1	v 1.5	d 0.4	v 2.8	d 0.0	v 2.3	d 0.1	Jupiter	108 55.5	1 07
										Saturn	5 55.1	7 58

Figure 2005. Left hand daily page of the *Nautical Almanac* for May 17, 1995.

h_c (computed)	47° 08.2'
h_o	47° 13.6'
a (intercept)	5.4 towards
Z	018.9°
Z_n	018.9°

2006. Reducing A Sun Sight

The example below points out the similarities between reducing a sun sight and reducing a star sight. It also demonstrates the additional corrections required for low altitude (<10°) sights and sights taken during non-standard temperature and pressure conditions.

On June 16, 1994, at 05-15-23 local time, at DR position L 30°N λ 45°W, a navigator takes a sight of the sun's upper limb. The navigator has a height of eye of 18 feet, the temperature is 88° F, and the atmospheric pressure is 982 mb. The sextant altitude is 3° 20.2'. There is no index error. Determine the observed altitude. See Figure 2007.

Body	Sun UL
Index Correction	0
Dip Correction (18 ft)	-4.1'
Sum	-4.1'
h_s	3° 20.2'
h_a	3° 16.1'
Altitude Correction	-29.4'
Additional Correction	+1.4'
Horizontal Parallax	0
Correction to h_a	-28.0'
h_o	2° 48.1'

Apply the index and dip corrections to h_s to obtain h_a. Because h_a is less than 10°, use the special altitude correction table for sights between 0° and 10° located on the right inside front page of the *Nautical Almanac*.

Enter the table with the apparent altitude, the limb of the sun used for the sight, and the period of the year. Interpolation for the apparent altitude is not required. In this case, the table yields a correction of -29.4'. The correction's algebraic sign is found at the head of each group of entries and at every change of sign.

The additional correction is required because of the non-standard temperature and atmospheric pressure under which the sight was taken. The correction for these non-standard conditions is found in the *Additional Corrections* table located on page A4 in the front of the *Nautical Almanac*.

First, enter the *Additional Corrections* table with the temperature and pressure to determine the correct zone letter: in this case, zone L. Then, locate the correction in the L column corresponding to the apparent altitude of 3° 16.1'. Interpolate between the table arguments of 3° 00.0' and 3° 30.0' to determine the additional correction: +1.4'. The total correction to the apparent altitude is the sum of the altitude and additional corrections: -28.0'. This results in an h_o of 2° 48.1'.

Next, determine the sun's GHA and declination. Again, this process is similar to the star sights reduced above. Notice, however, that SHA, a quantity unique to star sight reduction, is not used in sun sight reduction.

Date	June 16, 1994
DR Latitude	N30° 00.0'
DR Longitude	W045° 00.0'
Observation Time	05-15-23
Watch Error	0
Zone Time	05-15-23
Zone Description	+03
GMT	08-15-23
Date GMT	June 16, 1994
Tab GHA / *v*	299° 51.3' / n.a.
GHA Increment	3° 50.8'
SHA or *v* correction	not applicable
GHA	303°42.1'
Assumed Longitude	44° 42.1' W
LHA	259°
Tab Declination / *d*	N23° 20.5' / +0.1'
d Correction	0.0
True Declination	N23° 20.5'
Assumed Latitude	N30° (same)

Determining the sun's GHA is less complicated than determining a star's GHA. The *Nautical Almanac's* daily pages list the sun's GHA in hourly increments. In this case, the sun's GHA at 0800 GMT on June 16, 1994 is 299° 51.3'. The *v* correction is not applicable for a sun sight; therefore, applying the increment correction yields the sun's GHA. In this case, the GHA is 303° 42.1'.

Determining the sun's LHA is similar to determining a star's LHA. In determining the sun's declination, however, an additional correction not encountered in the star sight, the *d* correction, must be considered. The bottom of the sun column on the daily pages of the *Nautical Almanac* lists the *d* value. This is an interpolation factor for the sun's declination. The sign of the *d* factor is not given; it must be determined by noting from the *Almanac* if the sun's declination is increasing or decreasing throughout the day. If it is increasing, the factor is positive; if it is decreasing, the factor is negative. In the above problem, the sun's declination is increasing throughout the day. Therefore, the *d* factor is +0.1.

Having obtained the *d* factor, enter the 15 minute increment and correction table. Under the column labeled "*v* or *d* corr^n," find the value for *d* in the left hand column. The corresponding number in the right hand column is the correction; apply it to the tabulated declination. In this case, the correction corresponding to a *d* value of +0.1 is 0.0'.

The final step will be to determine h_c and Z_n. Enter the *Sight Reduction Tables* with an LHA of 259°, a declination of N23° 20.5', and an assumed latitude of 30°N.

Declination Increment / + or - *d*	20.5' / +31.5
Tabulated Altitude	2° 28.8'

1994 JUNE 15, 16, 17 (WED., THURS., FRI.)

	UT (GMT) d h	ARIES G.H.A. ° ′	VENUS −4.0 G.H.A. ° ′	VENUS Dec. ° ′	MARS +1.2 G.H.A. ° ′	MARS Dec. ° ′	JUPITER −2.3 G.H.A. ° ′	JUPITER Dec. ° ′	SATURN +1.0 G.H.A. ° ′	SATURN Dec. ° ′
	15 00	263 03.0	140 48.0	N22 09.1	218 59.0	N16 08.6	49 42.0	S12 03.8	278 39.3	S 8 31.9
	01	278 05.4	155 47.4	08.5	233 59.7	09.1	64 44.6	03.8	293 41.7	31.9
	02	293 07.9	170 46.7	07.9	249 00.3	09.7	79 47.2	03.7	308 44.1	31.9
	03	308 10.4	185 46.1	· · 07.3	264 01.0	· · 10.2	94 49.7	· · 03.7	323 46.6	· · 31.9
	04	323 12.8	200 45.5	06.7	279 01.6	10.8	109 52.3	03.7	338 49.0	31.9
	05	338 15.3	215 44.8	06.0	294 02.2	11.3	124 54.9	03.6	353 51.4	31.9
	06	353 17.8	230 44.2	N22 05.4	309 02.9	N16 11.9	139 57.5	S12 03.6	8 53.9	S 8 31.9
W	07	8 20.2	245 43.6	04.8	324 03.5	12.4	155 00.1	03.6	23 56.3	31.9
E	08	23 22.7	260 42.9	04.2	339 04.2	13.0	170 02.7	03.5	38 58.7	31.9
D	09	38 25.2	275 42.3	· · 03.5	354 04.8	· · 13.5	185 05.3	· · 03.5	54 01.1	· · 31.9
N	10	53 27.6	290 41.7	02.9	9 05.5	14.0	200 07.9	03.5	69 03.6	31.9
E	11	68 30.1	305 41.0	02.3	24 06.1	14.6	215 10.4	03.4	84 06.0	31.9
S	12	83 32.6	320 40.4	N22 01.6	39 06.8	N16 15.1	230 13.0	S12 03.4	99 08.4	S 8 31.9
D	13	98 35.0	335 39.8	01.0	54 07.4	15.7	245 15.6	03.4	114 10.9	31.9
A	14	113 37.5	350 39.2	22 00.4	69 08.1	16.2	260 18.2	03.3	129 13.3	31.9
Y	15	128 39.9	5 38.5	21 59.7	84 08.7	· · 16.8	275 20.8	· · 03.3	144 15.7	· · 31.9
	16	143 42.4	20 37.9	59.1	99 09.4	17.3	290 23.4	03.3	159 18.2	31.9
	17	158 44.9	35 37.3	58.5	114 10.0	17.8	305 26.0	03.3	174 20.6	31.9
	18	173 47.3	50 36.7	N21 57.8	129 10.7	N16 18.4	320 28.5	S12 03.2	189 23.0	S 8 31.9
	19	188 49.8	65 36.0	57.2	144 11.3	18.9	335 31.1	03.2	204 25.5	31.9
	20	203 52.3	80 35.4	56.6	159 12.0	19.5	350 33.7	03.2	219 27.9	31.9
	21	218 54.7	95 34.8	· · 55.9	174 12.6	· · 20.0	5 36.3	· · 03.1	234 30.3	· · 31.9
	22	233 57.2	110 34.2	55.3	189 13.3	20.6	20 38.9	03.1	249 32.8	31.9
	23	248 59.7	125 33.5	54.6	204 13.9	21.1	35 41.5	03.1	264 35.2	31.9
	16 00	264 02.1	140 32.9	N21 54.0	219 14.6	N16 21.6	50 44.1	S12 03.0	279 37.6	S 8 31.9
	01	279 04.6	155 32.3	53.4	234 15.2	22.2	65 46.6	03.0	294 40.1	31.9
	02	294 07.1	170 31.7	52.7	249 15.9	22.7	80 49.2	03.0	309 42.5	31.9
	03	309 09.5	185 31.1	· · 52.1	264 16.5	· · 23.2	95 51.8	· · 03.0	324 44.9	· · 31.9
	04	324 12.0	200 30.4	51.4	279 17.2	23.8	110 54.4	02.9	339 47.4	31.9
	05	339 14.4	215 29.8	50.8	294 17.8	24.3	125 57.0	02.9	354 49.8	31.8
	06	354 16.9	230 29.2	N21 50.1	309 18.5	N16 24.9	140 59.5	S12 02.9	9 52.2	S 8 31.8
	07	9 19.4	245 28.6	49.5	324 19.1	25.4	156 02.1	02.8	24 54.7	31.8
T	08	24 21.8	260 28.0	48.8	339 19.8	25.9	171 04.7	02.8	39 57.1	31.8
H	09	39 24.3	275 27.4	· · 48.2	354 20.4	· · 26.5	186 07.3	· · 02.8	54 59.5	· · 31.8
U	10	54 26.8	290 26.8	47.5	9 21.1	27.0	201 09.9	02.7	70 02.0	31.8
R	11	69 29.2	305 26.1	46.9	24 21.7	27.6	216 12.5	02.7	85 04.4	31.8
S	12	84 31.7	320 25.5	N21 46.2	39 22.3	N16 28.1	231 15.0	S12 02.7	100 06.8	S 8 31.8
D	13	99 34.2	335 24.9	45.6	54 23.0	28.6	246 17.6	02.7	115 09.3	31.8
A	14	114 36.6	350 24.3	44.9	69 23.6	29.2	261 20.2	02.6	130 11.7	31.8
Y	15	129 39.1	5 23.7	· · 44.3	84 24.3	· · 29.7	276 22.8	· · 02.6	145 14.1	· · 31.8
	16	144 41.5	20 23.1	43.6	99 24.9	30.2	291 25.3	02.6	160 16.6	31.8
	17	159 44.0	35 22.5	42.9	114 25.6	30.8	306 27.9	02.5	175 19.0	31.8
	18	174 46.5	50 21.9	N21 42.3	129 26.2	N16 31.3	321 30.5	S12 02.5	190 21.4	S 8 31.8
	19	189 48.9	65 21.3	41.6	144 26.9	31.8	336 33.1	02.5	205 23.9	31.8
	20	204 51.4	80 20.6	41.0	159 27.5	32.4	351 35.7	02.5	220 26.3	31.8
	21	219 53.9	95 20.0	· · 40.3	174 28.2	· · 32.9	6 38.2	· · 02.4	235 28.7	· · 31.8
	22	234 56.3	110 19.4	39.6	189 28.8	33.4	21 40.8	02.4	250 31.2	31.8
	23	249 58.8	125 18.8	39.0	204 29.5	34.0	36 43.4	02.4	265 33.6	31.8
	17 00	265 01.3	140 18.2	N21 38.3	219 30.1	N16 34.5	51 46.0	S12 02.4	280 36.0	S 8 31.8
	01	280 03.7	155 17.6	37.6	234 30.8	35.0	66 48.5	02.3	295 38.5	31.8
	02	295 06.2	170 17.0	37.0	249 31.4	35.6	81 51.1	02.3	310 40.9	31.8
	03	310 08.7	185 16.4	· · 36.3	264 32.1	· · 36.1	96 53.7	· · 02.3	325 43.4	· · 31.8
	04	325 11.1	200 15.8	35.6	279 32.7	36.6	111 56.3	02.2	340 45.8	31.8
	05	340 13.6	215 15.2	35.0	294 33.3	37.2	126 58.8	02.2	355 48.2	31.8
	06	355 16.0	230 14.6	N21 34.3	309 34.0	N16 37.7	142 01.4	S12 02.2	10 50.7	S 8 31.8
	07	10 18.5	245 14.0	33.6	324 34.6	38.2	157 04.0	02.2	25 53.1	31.8
	08	25 21.0	260 13.4	32.9	339 35.3	38.8	172 06.6	02.1	40 55.5	31.8
F	09	40 23.4	275 12.8	· · 32.3	354 35.9	· · 39.3	187 09.1	· · 02.1	55 58.0	· · 31.8
R	10	55 25.9	290 12.2	31.6	9 36.6	39.8	202 11.7	02.1	71 00.4	31.8
I	11	70 28.4	305 11.6	30.9	24 37.2	40.4	217 14.3	02.1	86 02.9	31.8
D	12	85 30.8	320 11.0	N21 30.2	39 37.9	N16 40.9	232 16.9	S12 02.0	101 05.3	S 8 31.8
A	13	100 33.3	335 10.4	29.6	54 38.5	41.4	247 19.4	02.0	116 07.7	31.8
Y	14	115 35.8	350 09.8	28.9	69 39.2	41.9	262 22.0	02.0	131 10.2	31.8
	15	130 38.2	5 09.2	· · 28.2	84 39.8	· · 42.5	277 24.6	· · 02.0	146 12.6	· · 31.8
	16	145 40.7	20 08.6	27.5	99 40.5	43.0	292 27.1	01.9	161 15.1	31.8
	17	160 43.2	35 08.0	26.8	114 41.1	43.5	307 29.7	01.9	176 17.5	31.8
	18	175 45.6	50 07.4	N21 26.2	129 41.7	N16 44.1	322 32.3	S12 01.9	191 19.9	S 8 31.8
	19	190 48.1	65 06.8	25.5	144 42.4	44.6	337 34.9	01.9	206 22.4	31.8
	20	205 50.5	80 06.2	24.8	159 43.0	45.1	352 37.4	01.8	221 24.8	31.8
	21	220 53.0	95 05.6	· · 24.1	174 43.7	· · 45.6	7 40.0	· · 01.8	236 27.3	· · 31.8
	22	235 55.5	110 05.1	23.4	189 44.3	46.2	22 42.6	01.8	251 29.7	31.8
	23	250 57.9	125 04.5	22.7	204 45.0	46.7	37 45.1	01.8	266 32.1	31.8
	Mer. Pass.	h m 6 22.8	v −0.6	d 0.7	v 0.6	d 0.5	v 2.6	d 0.0	v 2.4	d 0.0

STARS Name	S.H.A. ° ′	Dec. ° ′
Acamar	315 29.5	S40 19.5
Achernar	335 37.6	S57 15.6
Acrux	173 25.1	S63 04.5
Adhara	255 24.1	S28 58.0
Aldebaran	291 06.1	N16 29.8
Alioth	166 33.0	N55 59.6
Alkaid	153 09.8	N49 20.6
Al Na'ir	28 01.4	S46 58.9
Alnilam	276 01.2	S 1 12.4
Alphard	218 10.3	S 8 38.3
Alphecca	126 22.7	N26 44.1
Alpheratz	357 58.3	N29 03.5
Altair	62 21.8	N 8 51.3
Ankaa	353 29.8	S42 19.9
Antares	112 43.4	S26 25.2
Arcturus	146 08.5	N19 12.7
Atria	107 57.4	S69 01.1
Avior	234 24.3	S59 29.8
Bellatrix	278 47.6	N 6 20.6
Betelgeuse	271 17.0	N 7 24.3
Canopus	264 03.0	S52 41.7
Capella	280 56.0	N45 59.5
Deneb	49 40.8	N45 15.6
Denebola	182 48.1	N14 36.2
Diphda	349 10.3	S18 00.9
Dubhe	194 09.2	N61 47.0
Elnath	278 31.0	N28 36.1
Eltanin	90 52.2	N51 29.4
Enif	34 00.9	N 9 51.0
Fomalhaut	15 39.6	S29 38.8
Gacrux	172 16.6	S57 05.3
Gienah	176 06.9	S17 30.9
Hadar	149 07.7	S60 21.1
Hamal	328 17.1	N23 26.1
Kaus Aust.	84 02.3	S34 23.1
Kochab	137 18.6	N74 10.9
Markab	13 52.4	N15 10.5
Menkar	314 30.2	N 4 04.1
Menkent	148 24.1	S36 20.8
Miaplacidus	221 43.2	S69 42.1
Mirfak	309 01.2	N49 50.3
Nunki	76 15.6	S26 18.1
Peacock	53 41.1	S56 44.9
Pollux	243 45.4	N28 02.3
Procyon	245 14.9	N 5 14.2
Rasalhague	96 19.3	N12 33.9
Regulus	207 58.8	N11 59.6
Rigel	281 26.1	S 8 12.6
Rigil Kent.	140 10.7	S60 48.9
Sabik	102 28.5	S15 43.0
Schedar	349 56.9	N56 30.2
Shaula	96 40.8	S37 05.9
Sirius	258 46.6	S16 42.6
Spica	158 46.1	S11 08.1
Suhail	223 03.2	S43 24.9
Vega	80 48.2	N38 46.8
Zuben'ubi	137 20.9	S16 01.2

	S.H.A. ° ′	Mer. Pass. h m
Venus	236 30.8	14 38
Mars	315 12.5	9 23
Jupiter	146 41.9	20 34
Saturn	15 35.5	5 21

Figure 2006. Left hand daily page of the *Nautical Almanac* for June 16, 1994.

Correction (+ or -)	+10.8'
Computed Altitude (h_c)	2° 39.6'
Observed Altitude (h_o)	2° 48.1'
Intercept	8.5 NM (towards)
Z	064.7°
Z_n	064.7°

2007. Reducing A Moon Sight

The moon is easy to identify and is often visible during the day. However, the moon's proximity to the earth requires applying additional corrections to h_a to obtain h_o. This section will cover moon sight reduction.

At 10-00-00 GMT, June 16, 1994, the navigator obtains a sight of the moon's upper limb. H_s is 26° 06.7'. Height of eye is 18 feet; there is no index error. Determine h_o, the moon's GHA, and the moon's declination. See Figure 2007.

Body	Moon (UL)
Index Correction	0.0'
Dip (18 feet)	-4.1'
Sum	-4.1'
Sextant Altitude (h_s)	26° 06.7'
Apparent Altitude (h_a)	26° 02.6'
Altitude Correction	+60.5'
Additional Correction	0.0'
Horizontal Parallax (58.4)	+4.0'
Moon Upper Limb Correction	-30.0'
Correction to h_a	+34.5'
Observed Altitude (h_o)	26° 37.1'

This procedure demonstrates the extra corrections required for obtaining h_o for a moon sight. Apply the index and dip corrections and in the same manner as for star and sun sights. The altitude correction comes from tables located on the inside back covers of the *Nautical Almanac*.

In this case, the apparent altitude was 26° 02.6'. Enter the altitude correction table for the moon with the above apparent altitude. Interpolation is not required. The correction is +60.5'. The additional correction in this case is not applicable because the sight was taken under standard temperature and pressure conditions.

The horizontal parallax correction is unique to moon sights. The table for determining this HP correction is on the back inside cover of the *Nautical Almanac*. First, go to the daily page for June 16 at 10-00-00 GMT. In the column for the moon, find the HP correction factor corresponding to 10-00-00. Its value is 58.4. Take this value to the HP correction table on the inside back cover of the *Almanac*. Notice that the HP correction columns line up vertically with the moon altitude correction table columns. Find the HP correction column directly under the altitude correction table heading corresponding to the apparent altitude. Enter that column with the HP correction factor from the daily pages. The column has two sets of figures listed under "U" and "L" for upper and lower limb, respectively. In this case, trace down the "U" column until it intersects with the HP correction factor of 58.4. Interpolating between 58.2 and 58.5 yields a value of +4.0' for the horizontal parallax correction.

The final correction is a constant -30.0' correction to h_a applied only to sights of the moon's upper limb. This correction is always negative; apply it only to sights of the moon's upper limb, not its lower limb. The total correction to h_a is the sum of all the corrections; in this case, this total correction is +34.5 minutes.

To obtain the moon's GHA, enter the daily pages in the moon column and extract the applicable data just as for a star or sun sight. Determining the moon's GHA requires an additional correction, the *v* correction.

GHA moon and *v*	245° 45.1' and +11.3
GHA Increment	0° 00.0'
v Correction	+0.1'
GHA	245° 45.2'

First, record the GHA of the moon for 10-00-00 on June 16, 1994, from the daily pages of the *Nautical Almanac*. Record also the *v* correction factor; in this case, it is +11.3. The *v* correction factor for the moon is always positive. The increment correction is, in this case, zero because the sight was recorded on the even hour. To obtain the *v* correction, go to the tables of increments and corrections. In the 0 minute table in the *v* or *d* correction columns, find the correction that corresponds to a *v* = 11.3. The table yields a correction of +0.1'. Adding this correction to the tabulated GHA gives the final GHA as 245° 45.2'.

Finding the moon's declination is similar to finding the declination for the sun or stars. Go to the daily pages for June 16, 1994; extract the moon's declination and *d* factor.

Tabulated Declination / *d*	S 00° 13.7' / +12.1
d Correction	+0.1'
True Declination	S 00° 13.8'

The tabulated declination and the *d* factor come from the *Nautical Almanac's* daily pages. Record the declination and *d* correction and go to the increment and correction pages to extract the proper correction for the given *d* factor. In this case, go to the correction page for 0 minutes. The correction corresponding to a *d* factor of +12.1 is +0.1. It is important to extract the correction with the correct algebraic sign. The *d* correction may be positive or negative depending on whether the moon's declination is increasing or decreasing in the interval covered by the *d* factor. In this case, the moon's declination at 10-00-00 GMT on 16 June was S 00° 13.7'; at 11-00-00 on the same date the moon's declination was S 00° 25.8'. Therefore, since the declination was increasing over this period, the *d* correction is positive. Do not determine the sign of this correction by noting the trend in the *d* factor. In other words, had the *d* factor for 11-00-00 been a value less than 12.1, that would not indicate that the *d* correction should be negative. Remember that the *d* factor is analogous to an interpolation

1994 JUNE 15, 16, 17 (WED., THURS., FRI.)

UT (GMT) d	h	SUN G.H.A. ° ′	SUN Dec. ° ′	MOON G.H.A. ° ′	MOON v ′	MOON Dec. ° ′	MOON d ′	MOON H.P. ′
15	00	179 55.6	N23 17.2	112 24.4	11.8	N 6 28.5	11.4	57.6
	01	194 55.5	17.4	126 55.2	11.8	6 17.1	11.3	57.6
	02	209 55.4	17.5	141 26.0	11.8	6 05.8	11.4	57.6
	03	224 55.2	. . 17.6	155 56.8	11.7	5 54.4	11.4	57.7
	04	239 55.1	17.7	170 27.5	11.8	5 43.0	11.5	57.7
	05	254 55.0	17.8	184 58.3	11.8	5 31.5	11.5	57.7
	06	269 54.8	N23 17.9	199 29.1	11.7	N 5 20.0	11.6	57.7
W	07	284 54.7	18.0	213 59.8	11.8	5 08.4	11.5	57.8
E	08	299 54.6	18.1	228 30.6	11.7	4 56.9	11.7	57.8
D	09	314 54.4	. . 18.2	243 01.3	11.8	4 45.2	11.6	57.8
N	10	329 54.3	18.3	257 32.1	11.7	4 33.6	11.7	57.8
E	11	344 54.2	18.5	272 02.8	11.7	4 21.9	11.7	57.9
S	12	359 54.0	N23 18.6	286 33.5	11.7	N 4 10.2	11.8	57.9
D	13	14 53.9	18.7	301 04.2	11.7	3 58.4	11.7	57.9
A	14	29 53.8	18.8	315 34.9	11.7	3 46.7	11.8	57.9
Y	15	44 53.6	. . 18.9	330 05.6	11.7	3 34.9	11.9	58.0
	16	59 53.5	19.0	344 36.3	11.6	3 23.0	11.8	58.0
	17	74 53.4	19.1	359 06.9	11.6	3 11.2	11.9	58.0
	18	89 53.2	N23 19.2	13 37.5	11.7	N 2 59.3	11.9	58.0
	19	104 53.1	19.3	28 08.2	11.6	2 47.4	12.0	58.1
	20	119 53.0	19.4	42 38.8	11.6	2 35.4	11.9	58.1
	21	134 52.8	. . 19.5	57 09.4	11.5	2 23.5	12.0	58.1
	22	149 52.7	19.6	71 39.9	11.6	2 11.5	12.0	58.1
	23	164 52.6	19.7	86 10.5	11.5	1 59.5	12.0	58.2
16	00	179 52.4	N23 19.8	100 41.0	11.5	N 1 47.5	12.1	58.2
	01	194 52.3	19.9	115 11.5	11.5	1 35.4	12.0	58.2
	02	209 52.2	20.0	129 42.0	11.5	1 23.4	12.1	58.2
	03	224 52.0	. . 20.1	144 12.5	11.5	1 11.3	12.1	58.3
	04	239 51.9	20.1	158 43.0	11.4	0 59.2	12.1	58.3
	05	254 51.7	20.2	173 13.4	11.4	0 47.1	12.1	58.3
	06	269 51.6	N23 20.3	187 43.8	11.4	N 0 35.0	12.2	58.3
	07	284 51.5	20.4	202 14.2	11.3	0 22.8	12.1	58.4
T	08	299 51.3	20.5	216 44.5	11.3	N 0 10.7	12.2	58.4
H	09	314 51.2	. . 20.6	231 14.8	11.3	S 0 01.5	12.2	58.4
U	10	329 51.1	20.7	245 45.1	11.3	0 13.7	12.1	58.4
R	11	344 50.9	20.8	260 15.4	11.2	0 25.8	12.2	58.5
S	12	359 50.8	N23 20.9	274 45.6	11.3	S 0 38.0	12.2	58.5
D	13	14 50.7	21.0	289 15.9	11.1	0 50.2	12.2	58.5
A	14	29 50.5	21.1	303 46.0	11.2	1 02.4	12.2	58.5
Y	15	44 50.4	. . 21.1	318 16.2	11.1	1 14.6	12.2	58.6
	16	59 50.3	21.2	332 46.3	11.1	1 26.8	12.3	58.6
	17	74 50.1	21.3	347 16.4	11.0	1 39.1	12.2	58.6
	18	89 50.0	N23 21.4	1 46.4	11.0	S 1 51.3	12.2	58.6
	19	104 49.9	21.5	16 16.4	11.0	2 03.5	12.2	58.7
	20	119 49.7	21.6	30 46.4	10.9	2 15.7	12.2	58.7
	21	134 49.6	. . 21.6	45 16.3	10.9	2 27.9	12.2	58.7
	22	149 49.5	21.7	59 46.2	10.9	2 40.1	12.2	58.7
	23	164 49.3	21.8	74 16.1	10.8	2 52.3	12.2	58.8
17	00	179 49.2	N23 21.9	88 45.9	10.8	S 3 04.5	12.2	58.8
	01	194 49.1	22.0	103 15.7	10.7	3 16.7	12.2	58.8
	02	209 48.9	22.0	117 45.4	10.7	3 28.9	12.2	58.8
	03	224 48.8	. . 22.1	132 15.1	10.7	3 41.1	12.2	58.9
	04	239 48.6	22.2	146 44.8	10.6	3 53.3	12.1	58.9
	05	254 48.5	22.3	161 14.4	10.6	4 05.4	12.2	58.9
	06	269 48.4	N23 22.3	175 44.0	10.5	S 4 17.6	12.1	58.9
	07	284 48.2	22.4	190 13.5	10.5	4 29.7	12.1	59.0
	08	299 48.1	22.5	204 43.0	10.4	4 41.8	12.1	59.0
F	09	314 48.0	. . 22.6	219 12.4	10.4	4 53.9	12.1	59.0
R	10	329 47.8	22.6	233 41.8	10.3	5 06.0	12.1	59.0
I	11	344 47.7	22.7	248 11.1	10.3	5 18.1	12.1	59.1
D	12	359 47.6	N23 22.8	262 40.4	10.2	S 5 30.2	12.0	59.1
A	13	14 47.4	22.9	277 09.6	10.2	5 42.2	12.0	59.1
Y	14	29 47.3	22.9	291 38.8	10.1	5 54.2	12.0	59.1
	15	44 47.2	. . 23.0	306 07.9	10.1	6 06.2	11.9	59.2
	16	59 47.0	23.1	320 37.0	10.0	6 18.1	12.0	59.2
	17	74 46.9	23.1	335 06.0	10.0	6 30.1	11.9	59.2
	18	89 46.8	N23 23.2	349 35.0	9.9	S 6 42.0	11.9	59.2
	19	104 46.6	23.3	4 03.9	9.9	6 53.9	11.8	59.3
	20	119 46.5	23.3	18 32.8	9.8	7 05.7	11.8	59.3
	21	134 46.3	. . 23.4	33 01.6	9.7	7 17.5	11.8	59.3
	22	149 46.2	23.5	47 30.3	9.7	7 29.3	11.8	59.3
	23	164 46.1	23.5	61 59.0	9.6	7 41.1	11.7	59.4
		S.D. 15.8	d 0.1	S.D.	15.8		15.9	16.1

Lat. °	Twilight Naut. h m	Twilight Civil h m	Sunrise h m	Moonrise 15 h m	Moonrise 16 h m	Moonrise 17 h m	Moonrise 18 h m
N 72	□	□	□	09 54	11 50	13 49	15 56
N 70	□	□	□	10 01	11 49	13 40	15 36
68	□	□	□	10 06	11 48	13 33	15 21
66	□	□	□	10 11	11 47	13 26	15 09
64	////	////	01 33	10 14	11 47	13 21	14 59
62	////	////	02 10	10 18	11 46	13 17	14 50
60	////	00 52	02 36	10 20	11 46	13 13	14 43
N 58	////	01 41	02 56	10 23	11 45	13 10	14 37
56	////	02 11	03 13	10 25	11 45	13 07	14 31
54	00 48	02 33	03 27	10 27	11 45	13 04	14 26
52	01 33	02 51	03 39	10 29	11 44	13 02	14 21
50	02 00	03 06	03 50	10 30	11 44	13 00	14 17
45	02 46	03 35	04 13	10 34	11 44	12 55	14 08
N 40	03 16	03 58	04 31	10 37	11 43	12 51	14 01
35	03 39	04 16	04 46	10 39	11 43	12 48	13 54
30	03 58	04 31	04 59	10 42	11 42	12 45	13 49
20	04 27	04 56	05 20	10 45	11 42	12 40	13 39
N 10	04 49	05 16	05 39	10 49	11 41	12 35	13 31
0	05 08	05 34	05 57	10 52	11 41	12 31	13 23
S 10	05 25	05 51	06 14	10 55	11 40	12 27	13 16
20	05 41	06 09	06 33	10 59	11 40	12 23	13 07
30	05 58	06 28	06 54	11 03	11 40	12 18	12 58
35	06 06	06 38	07 06	11 05	11 39	12 15	12 53
40	06 16	06 50	07 20	11 07	11 39	12 12	12 47
45	06 26	07 03	07 37	11 10	11 39	12 08	12 40
S 50	06 38	07 19	07 58	11 14	11 38	12 04	12 32
52	06 43	07 27	08 08	11 15	11 38	12 02	12 28
54	06 49	07 35	08 19	11 17	11 38	12 00	12 24
56	06 55	07 44	08 31	11 19	11 38	11 58	12 19
58	07 02	07 54	08 46	11 21	11 38	11 55	12 14
S 60	07 09	08 06	09 03	11 24	11 37	11 52	12 09

Lat. °	Sunset h m	Twilight Civil h m	Twilight Naut. h m	Moonset 15 h m	Moonset 16 h m	Moonset 17 h m	Moonset 18 h m
N 72	□	□	□	23 38	23 25	23 12	22 54
N 70	□	□	□	23 35	23 29	23 23	23 16
68	□	□	□	23 34	23 33	23 32	23 32
66	□	□	□	23 32	23 36	23 40	23 46
64	22 29	////	////	23 31	23 38	23 47	23 57
62	21 52	////	////	23 29	23 40	23 52	24 07
60	21 26	23 10	////	23 28	23 42	23 57	24 15
N 58	21 05	22 21	////	23 27	23 44	24 02	00 02
56	20 49	21 51	////	23 26	23 45	24 06	00 06
54	20 34	21 29	23 15	23 26	23 47	24 09	00 09
52	20 22	21 11	22 29	23 25	23 48	24 13	00 13
50	20 11	20 56	22 01	23 24	23 49	24 15	00 15
45	19 49	20 26	21 16	23 23	23 52	24 22	00 22
N 40	19 31	20 04	20 45	23 22	23 54	24 27	00 27
35	19 16	19 45	20 22	23 21	23 55	24 32	00 32
30	19 03	19 30	20 04	23 20	23 57	24 36	00 36
20	18 41	19 05	19 35	23 18	24 00	00 00	00 43
N 10	18 22	18 45	19 12	23 17	24 02	00 02	00 50
0	18 04	18 27	18 53	23 15	24 05	00 05	00 55
S 10	17 47	18 10	18 36	23 14	24 07	00 07	01 01
20	17 28	17 52	18 20	23 12	24 09	00 09	01 08
30	17 07	17 34	18 03	23 10	24 12	00 12	01 15
35	16 55	17 23	17 55	23 09	24 13	00 13	01 19
40	16 41	17 11	17 45	23 08	24 15	00 15	01 24
45	16 24	16 58	17 35	23 07	24 17	00 17	01 29
S 50	16 03	16 42	17 23	23 05	24 20	00 20	01 36
52	15 53	16 34	17 18	23 04	24 21	00 21	01 39
54	15 42	16 26	17 12	23 04	24 22	00 22	01 42
56	15 30	16 17	17 06	23 03	24 23	00 23	01 46
58	15 15	16 07	16 59	23 02	24 25	00 25	01 50
S 60	14 58	15 55	16 52	23 00	24 27	00 27	01 55

Day	SUN Eqn. of Time 00h m s	SUN Eqn. of Time 12h m s	SUN Mer. Pass. h m	MOON Mer. Pass. Upper h m	MOON Mer. Pass. Lower h m	MOON Age d	MOON Phase
15	00 17	00 24	12 00	17 04	04 39	06	
16	00 30	00 37	12 01	17 53	05 28	07	
17	00 43	00 49	12 01	18 43	06 18	08	

Figure 2007. Right hand daily page of the *Nautical Almanac* for June 16, 1994.

factor; it provides a correction to declination. Therefore, the trend in declination values, not the trend in *d* values, controls the sign of the *d* correction. Combine the tabulated declination and the *d* correction factor to determine the true declination. In this case, the moon's true declination is S 00° 13.8'

Having obtained the moon's GHA and declination, calculate LHA and determine the assumed latitude. Enter the *Sight Reduction Table* with the LHA, assumed latitude, and calculated declination. Calculate the intercept and azimuth in the same manner used for star and sun sights.

2008. Reducing A Planet Sight

There are four navigational planets: Venus, Mars, Jupiter, and Saturn. Reducing a planet sight is similar to reducing a sun or star sight, but there are a few important differences. This section will cover the procedure for determining h_o, the GHA and the declination for a planet sight.

On July 27, 1995, at 09-45-20 GMT, you take a sight of Mars. H_s is 33° 20.5'. The height of eye is 25 feet, and the index correction is +0.2'. Determine h_o, GHA, and declination. See Figure 2008.

Body	Mars
Index Correction	+0.2'
Dip Correction (25 feet)	-4.9'
Sum	-4.7'
h_s	33° 20.5'
h_a	33° 15.8'
Altitude Correction	-1.5'
Additional Correction	Not applicable
Horizontal Parallax	Not applicable
Additional Correction for Mars	+0.1'
Correction to h_a	-1.4'
h_o	33° 14.4'

The table above demonstrates the similarity between reducing planet sights and reducing sights of the sun and stars. Calculate and apply the index and dip corrections exactly as for any other sight. Take the resulting apparent altitude and enter the altitude correction table for the stars and planets on the inside front cover of the *Nautical Almanac*.

In this case, the altitude correction for 33° 15.8' results in a correction of -1.5'. The additional correction is not applicable because the sight was taken at standard temperature and pressure; the horizontal parallax correction is not applicable to a planet sight. All that remains is the correction specific to Mars or Venus. The altitude correction table in the *Nautical Almanac* also contains this correction. Its magnitude is a function of the body sighted (Mars or Venus), the time of year, and the body's apparent altitude. Entering this table with the data for this problem yields a correction of +0.1'. Applying these corrections to h_a results in an h_o of 33° 14.4'.

Tabulated GHA / *v*	256°10.6' / 1.1
GHA Increment	11° 20.0'
v correction	+0.8'
GHA	267°31.4'

The only difference between determining the sun's GHA and a planet's GHA lies in applying the *v* correction. Calculate this correction from the *v* or *d* correction section of the Increments and Correction table in the *Nautical Almanac*.

Find the *v* factor at the bottom of the planets' GHA columns on the daily pages of the *Nautical Almanac*. For Mars on July 27, 1995, the *v* factor is 1.1. If no algebraic sign precedes the *v* factor, add the resulting correction to the tabulated GHA. Subtract the resulting correction only when a negative sign precedes the *v* factor. Entering the *v* or *d* correction table corresponding to 45 minutes yields a correction of 0.8'. Remember, because no sign preceded the *v* factor on the daily pages, add this correction to the tabulated GHA. The final GHA is 267°31.4'.

Tabulated Declination / *d*	S 01° 06.1' / 0.6
d Correction	+0.5'
True Declination	S 01° 06.6'

Read the tabulated declination directly from the daily pages of the *Nautical Almanac*. The *d* correction factor is listed at the bottom of the planet column; in this case, the factor is 0.6. Note the trend in the declination values for the planet; if they are increasing during the day, the correction factor is positive. If the planet's declination is decreasing during the day, the correction factor is negative. Next, enter the *v* or *d* correction table corresponding to 45 minutes and extract the correction for a *d* factor of 0.6. The correction in this case is +0.5'.

From this point, reducing a planet sight is exactly the same as reducing a sun sight.

MERIDIAN PASSAGE

This section covers determining both latitude and longitude at the meridian passage of the sun, or Local Apparent Noon (LAN). Determining a vessel's latitude at LAN requires calculating the sun's zenith distance and declination and combining them according to the rules discussed below.

Latitude at LAN is a special case of the navigational triangle where the sun is on the observer's meridian and the triangle becomes a straight north/south line. No "solution" is necessary, except to combine the sun's zenith distance and its declination according to the rules discussed below.

Longitude at LAN is a function of the time elapsed since the sun passed the Greenwich meridian. The navigator must determine the time of LAN and calculate the GHA of the sun at that time. The following examples demonstrates these processes.

1995 JULY 27, 28, 29 (THURS., FRI., SAT.)

UT (GMT) d h		ARIES G.H.A.	VENUS −3.9 G.H.A.	VENUS Dec.	MARS +1.3 G.H.A.	MARS Dec.	JUPITER −2.3 G.H.A.	JUPITER Dec.	SATURN +1.0 G.H.A.	SATURN Dec.
		° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
27 00		304 12.4	185 23.5	N21 31.7	121 00.7	S 1 00.4	60 23.8	S20 36.7	308 27.9	S 4 15.6
01		319 14.9	200 22.7	31.2	136 01.8	01.0	75 26.3	36.7	323 30.4	15.7
02		334 17.3	215 21.9	30.7	151 02.9	01.7	90 28.8	36.7	338 33.0	15.7
03		349 19.8	230 21.1	· · 30.2	166 04.0	· · 02.3	105 31.3	· · 36.7	353 35.5	· · 15.8
04		4 22.3	245 20.4	29.7	181 05.1	02.9	120 33.8	36.7	8 38.1	15.8
05		19 24.7	260 19.6	29.2	196 06.2	03.6	135 36.4	36.7	23 40.6	15.8
06		34 27.2	275 18.8	N21 28.7	211 07.3	S 1 04.2	150 38.9	S20 36.7	38 43.1	S 4 15.9
07		49 29.7	290 18.0	28.2	226 08.4	04.8	165 41.4	36.7	53 45.7	15.9
08	T	64 32.1	305 17.2	27.7	241 09.5	05.4	180 43.9	36.7	68 48.2	16.0
09	H	79 34.6	320 16.4	· · 27.1	256 10.6	· · 06.1	195 46.4	· · 36.7	83 50.7	· · 16.0
10	U	94 37.1	335 15.6	26.6	271 11.7	06.7	210 48.9	36.7	98 53.3	16.1
11	R	109 39.5	350 14.8	26.1	286 12.8	07.3	225 51.5	36.7	113 55.8	16.1
12	S	124 42.0	5 14.0	N21 25.6	301 13.9	S 1 08.0	240 54.0	S20 36.7	128 58.4	S 4 16.1
13	D	139 44.4	20 13.2	25.1	316 15.0	08.6	255 56.5	36.7	144 00.9	16.2
14	A	154 46.9	35 12.4	24.5	331 16.1	09.2	270 59.0	36.7	159 03.4	16.2
15	Y	169 49.4	50 11.6	· · 24.0	346 17.2	· · 09.8	286 01.5	· · 36.7	174 06.0	· · 16.3
16		184 51.8	65 10.8	23.5	1 18.3	10.5	301 04.0	36.7	189 08.5	16.3
17		199 54.3	80 10.0	23.0	16 19.4	11.1	316 06.6	36.7	204 11.1	16.4
18		214 56.8	95 09.2	N21 22.5	31 20.6	S 1 11.7	331 09.1	S20 36.7	219 13.6	S 4 16.4
19		229 59.2	110 08.4	21.9	46 21.7	12.4	346 11.6	36.7	234 16.1	16.4
20		245 01.7	125 07.7	21.4	61 22.8	13.0	1 14.1	36.7	249 18.7	16.5
21		260 04.2	140 06.9	· · 20.9	76 23.9	· · 13.6	16 16.6	· · 36.7	264 21.2	· · 16.5
22		275 06.6	155 06.1	20.3	91 25.0	14.2	31 19.1	36.7	279 23.8	16.6
23		290 09.1	170 05.3	19.8	106 26.1	14.9	46 21.6	36.7	294 26.3	16.6
28 00		305 11.6	185 04.5	N21 19.3	121 27.2	S 1 15.5	61 24.1	S20 36.7	309 28.8	S 4 16.7
01		320 14.0	200 03.7	18.8	136 28.3	16.1	76 26.7	36.7	324 31.4	16.7
02		335 16.5	215 02.9	18.2	151 29.4	16.8	91 29.2	36.7	339 33.9	16.8
03		350 18.9	230 02.1	· · 17.7	166 30.5	· · 17.4	106 31.7	· · 36.7	354 36.5	· · 16.8
04		5 21.4	245 01.3	17.1	181 31.6	18.0	121 34.2	36.7	9 39.0	16.8
05		20 23.9	260 00.6	16.6	196 32.7	18.6	136 36.7	36.7	24 41.5	16.9
06		35 26.3	274 59.8	N21 16.1	211 33.8	S 1 19.3	151 39.2	S20 36.7	39 44.1	S 4 16.9
07		50 28.8	289 59.0	15.5	226 34.9	19.9	166 41.7	36.7	54 46.6	17.0
08		65 31.3	304 58.2	15.0	241 36.0	20.5	181 44.2	36.7	69 49.2	17.0
09	F	80 33.7	319 57.4	· · 14.5	256 37.1	· · 21.2	196 46.7	· · 36.7	84 51.7	· · 17.1
10	R	95 36.2	334 56.6	13.9	271 38.2	21.8	211 49.2	36.7	99 54.3	17.1
11	I	110 38.7	349 55.8	13.4	286 39.3	22.4	226 51.8	36.7	114 56.8	17.2
12	D	125 41.1	4 55.1	N21 12.8	301 40.4	S 1 23.0	241 54.3	S20 36.7	129 59.3	S 4 17.2
13	A	140 43.6	19 54.3	12.3	316 41.5	23.7	256 56.8	36.7	145 01.9	17.2
14	Y	155 46.1	34 53.5	11.7	331 42.6	24.3	271 59.3	36.7	160 04.4	17.3
15		170 48.5	49 52.7	· · 11.2	346 43.6	· · 24.9	287 01.8	· · 36.7	175 07.0	· · 17.3
16		185 51.0	64 51.9	10.6	1 44.7	25.6	302 04.3	36.7	190 09.5	17.4
17		200 53.4	79 51.1	10.1	16 45.8	26.2	317 06.8	36.7	205 12.1	17.4
18		215 55.9	94 50.4	N21 09.5	31 46.9	S 1 26.8	332 09.3	S20 36.7	220 14.6	S 4 17.5
19		230 58.4	109 49.6	09.0	46 48.0	27.5	347 11.8	36.7	235 17.1	17.5
20		246 00.8	124 48.8	08.4	61 49.1	28.1	2 14.3	36.7	250 19.7	17.6
21		261 03.3	139 48.0	· · 07.9	76 50.2	· · 28.7	17 16.8	· · 36.7	265 22.2	· · 17.6
22		276 05.8	154 47.2	07.3	91 51.3	29.3	32 19.3	36.7	280 24.8	17.6
23		291 08.2	169 46.4	06.8	106 52.4	30.0	47 21.8	36.7	295 27.3	17.7
29 00		306 10.7	184 45.7	N21 06.2	121 53.5	S 1 30.6	62 24.3	S20 36.8	310 29.9	S 4 17.7
01		321 13.2	199 44.9	05.7	136 54.6	31.2	77 26.8	36.8	325 32.4	17.8
02		336 15.6	214 44.1	05.1	151 55.7	31.9	92 29.3	36.8	340 34.9	17.8
03		351 18.1	229 43.3	· · 04.5	166 56.8	· · 32.5	107 31.8	· · 36.8	355 37.5	· · 17.9
04		6 20.5	244 42.5	04.0	181 57.9	33.1	122 34.3	36.8	10 40.0	17.9
05		21 23.0	259 41.8	03.4	196 59.0	33.8	137 36.8	36.8	25 42.6	18.0
06		36 25.5	274 41.0	N21 02.9	212 00.1	S 1 34.4	152 39.3	S20 36.8	40 45.1	S 4 18.0
07		51 27.9	289 40.2	02.3	227 01.2	35.0	167 41.8	36.8	55 47.7	18.1
08	S	66 30.4	304 39.4	01.7	242 02.3	35.6	182 44.4	36.8	70 50.2	18.1
09	A	81 32.9	319 38.7	· · 01.2	257 03.4	· · 36.3	197 46.9	· · 36.8	85 52.8	· · 18.1
10	T	96 35.3	334 37.9	00.6	272 04.5	36.9	212 49.4	36.8	100 55.3	18.2
11	U	111 37.8	349 37.1	21 00.0	287 05.6	37.5	227 51.9	36.8	115 57.9	18.2
12	R	126 40.3	4 36.3	N20 59.4	302 06.7	S 1 38.2	242 54.4	S20 36.8	131 00.4	S 4 18.3
13	D	141 42.7	19 35.6	58.9	317 07.8	38.8	257 56.9	36.8	146 02.9	18.3
14	A	156 45.2	34 34.8	58.3	332 08.9	39.4	272 59.4	36.8	161 05.5	18.4
15	Y	171 47.7	49 34.0	· · 57.7	347 10.0	· · 40.1	288 01.8	· · 36.8	176 08.0	· · 18.4
16		186 50.1	64 33.2	57.2	2 11.0	40.7	303 04.3	36.8	191 10.6	18.5
17		201 52.6	79 32.5	56.6	17 12.1	41.3	318 06.8	36.8	206 13.1	18.5
18		216 55.0	94 31.7	N20 56.0	32 13.2	S 1 42.0	333 09.3	S20 36.8	221 15.7	S 4 18.6
19		231 57.5	109 30.9	55.4	47 14.3	42.6	348 11.8	36.8	236 18.2	18.6
20		247 00.0	124 30.1	54.9	62 15.4	43.2	3 14.3	36.8	251 20.8	18.6
21		262 02.4	139 29.4	· · 54.3	77 16.5	· · 43.8	18 16.8	· · 36.8	266 23.3	· · 18.7
22		277 04.9	154 28.6	53.7	92 17.6	44.5	33 19.3	36.8	281 25.9	18.7
23		292 07.4	169 27.8	53.1	107 18.7	45.1	48 21.8	36.8	296 28.4	18.8
Mer. Pass.		h m 3 38.6	v −0.8	d 0.5	v 1.1	d 0.6	v 2.5	d 0.0	v 2.5	d 0.0

STARS Name	S.H.A.	Dec.
	° ′	° ′
Acamar	315 28.7	S40 19.1
Achernar	335 36.7	S57 15.2
Acrux	173 24.6	S63 04.8
Adhara	255 23.4	S28 58.0
Aldebaran	291 05.0	N16 29.9
Alioth	166 32.7	N55 59.3
Alkaid	153 09.6	N49 20.4
Al Na'ir	28 00.2	S46 58.7
Alnilam	276 00.3	S 1 12.3
Alphard	218 09.6	S 8 38.4
Alphecca	126 22.3	N26 44.0
Alpheratz	357 57.2	N29 04.0
Altair	62 21.0	N 8 51.6
Ankaa	353 28.8	S42 19.5
Antares	112 42.5	S26 25.3
Arcturus	146 08.0	N19 12.5
Atria	107 56.1	S69 01.3
Avior	234 24.1	S59 29.8
Bellatrix	278 46.7	N 6 20.7
Betelgeuse	271 16.1	N 7 24.3
Canopus	264 02.6	S52 41.6
Capella	280 54.7	N45 59.4
Deneb	49 40.1	N45 16.0
Denebola	182 47.6	N14 35.9
Diphda	349 09.2	S18 00.4
Dubhe	194 08.7	N61 46.6
Elnath	278 29.9	N28 36.1
Eltanin	90 51.9	N51 29.7
Enif	34 00.0	N 9 51.5
Fomalhaut	15 38.5	S29 38.5
Gacrux	172 16.1	S57 05.6
Gienah	176 06.3	S17 31.1
Hadar	149 07.0	S60 21.3
Hamal	328 15.9	N23 26.4
Kaus Aust.	84 01.3	S34 23.1
Kochab	137 19.4	N74 10.8
Markab	13 51.5	N15 11.0
Menkar	314 29.2	N 4 04.4
Menkent	148 23.4	S36 21.0
Miaplacidus	221 43.3	S69 42.1
Mirfak	308 59.8	N49 50.5
Nunki	76 14.6	S26 18.0
Peacock	53 39.8	S56 44.8
Pollux	243 44.5	N28 02.1
Procyon	245 14.1	N 5 14.1
Rasalhague	96 18.7	N12 34.0
Regulus	207 58.1	N11 59.3
Rigel	281 25.2	S 8 12.4
Rigil Kent.	140 10.0	S60 49.2
Sabik	102 27.7	S15 43.1
Schedar	349 55.6	N56 30.6
Shaula	96 39.8	S37 06.0
Sirius	258 45.9	S16 42.6
Spica	158 45.5	S11 08.3
Suhail	223 02.7	S43 25.0
Vega	80 47.7	N38 47.1
Zuben'ubi	137 20.3	S16 01.4

	S.H.A.	Mer. Pass.
	° ′	h m
Venus	239 52.9	11 40
Mars	176 15.6	15 53
Jupiter	116 12.6	19 51
Saturn	4 17.3	3 22

Figure 2008. Left hand daily page of the *Nautical Almanac* for July 27, 1995.

2009. Latitude At Meridian Passage

At 1056 ZT, May 16, 1995, a vessel's DR position is L 40° 04.3'N and λ 157° 18.5' W. The ship is on course 200°T at a speed of ten knots. (1) Calculate the first and second estimates of Local Apparent Noon. (2) The navigator actually observes LAN at 12-23-30 zone time. The sextant altitude at LAN is 69° 16.0'. The index correction is +2.1' and the height of eye is 45 feet. Determine the vessel's latitude.

Date	16 May 1995
DR Latitude (1156 ZT)	39° 55.0' N
DR Longitude (1156 ZT)	157° 23.0' W
Central Meridian	150° W
d Longitude (arc)	7° 23' W
d Longitude (time)	+29 min. 32 sec
Meridian Passage (LMT)	1156
ZT (first estimate)	12-25-32
DR Longitude (12-25-32)	157° 25.2'
d Longitude (arc)	7° 25.2'
d Longitude (time)	+29 min. 41 sec
Meridian Passage	1156
ZT (second estimate)	12-25-41
ZT (actual transit)	12-23-30 local
Zone Description	+10
GMT	22-23-30
Date (GMT)	16 May 1995
Tabulated Declination / *d*	N 19° 09.0' / +0.6
d correction	+0.2'
True Declination	N 19° 09.2'
Index Correction	+2.1'
Dip (48 ft)	-6.7'
Sum	-4.6'
h_s (at LAN)	69° 16.0'
h_a	69° 11.4'
Altitude Correction	+15.6'
89° 60'	89° 60.0'
h_o	69° 27.0'
Zenith Distance	N 20° 33.0'
True Declination	N 19° 09.2'
Latitude	39° 42.2'

First, determine the time of meridian passage from the daily pages of the *Nautical Almanac*. In this case, the meridian passage for May 16, 1995, is 1156. That is, the sun crosses the central meridian of the time zone at 1156 ZT and the observer's local meridian at 1156 local time. Next, determine the vessel's DR longitude for the time of meridian passage. In this case, the vessel's 1156 DR longitude is 157° 23.0' W. Determine the time zone in which this DR longitude falls and record the longitude of that time zone's central meridian. In this case, the central meridian is 150° W. Enter the Conversion of Arc to Time table in the *Nautical Almanac* with the difference between the DR longitude and the central meridian longitude. The conversion for 7° of arc is 28^m of time, and the conversion for 23' of arc is 1^m32^s of time. Sum these two times. If the DR position is west of the central meridian (as it is in this case), add this time to the time of tabulated meridian passage. If the longitude difference is to the east of the central meridian, subtract this time from the tabulated meridian passage. In this case, the DR position is west of the central meridian. Therefore, add 29 minutes and 32 seconds to 1156, the tabulated time of meridian passage. The estimated time of LAN is 12-25-32 ZT.

This first estimate for LAN does not take into account the vessel's movement. To calculate the *second estimate* of LAN, first determine the DR longitude for the time of first estimate of LAN (12-25-32 ZT). In this case, that longitude would be 157° 25.2' W. Then, calculate the difference between the longitude of the 12-25-32 DR position and the central meridian longitude. This would be 7° 25.2'. Again, enter the arc to time conversion table and calculate the time difference corresponding to this longitude difference. The correction for 7° of arc is 28' of time, and the correction for 25.2' of arc is 1'41'' of time. Finally, apply this time correction to the original tabulated time of meridian passage (1156 ZT). The resulting time, 12-25-41 ZT, is the *second estimate* of LAN.

Solving for latitude requires that the navigator calculate two quantities: the sun's declination and the sun's zenith distance. First, calculate the sun's true declination at LAN. The problem states that LAN is 12-28-30. (Determining the exact time of LAN is covered in section 2010.) Enter the time of observed LAN and add the correct zone description to determine GMT. Determine the sun's declination in the same manner as in the sight reduction problem in section 2006. In this case, the tabulated declination was N 19° 19.1', and the d correction +0.2'. The true declination, therefore, is N 19° 19.3'.

Next, calculate zenith distance. Recall from Navigational Astronomy that zenith distance is simply 90° - observed altitude. Therefore, correct h_s to obtain h_a; then correct h_a to obtain h_o. Then, subtract h_o from 90° to determine the zenith distance. Name the zenith distance North or South depending on the relative position of the observer and the sun's declination. If the observer is to the north of the sun's declination, name the zenith distance north. Conversely, if the observer is to the south of the sun's declination, name the zenith distance south. In this case, the DR latitude is N 39° 55.0' and the sun's declination is N 19° 19.3'. The observer is to the north of the sun's declination; therefore, name the zenith distance north. Next, compare the names of the zenith distance and the declination. If their names are the same (i.e., both are north or both are south), add the two values together to obtain the latitude. This was the case in this problem. Both the sun's declination and zenith distance were north; therefore, the observer's latitude is the sum of the two.

If the name of the body's zenith distance is contrary to the name of the sun's declination, then subtract the smaller of the two quantities from the larger, carrying for the name of the difference the name of the larger of the two quantities. The result is the observer's latitude. The following examples illustrate this process.

Zenith Distance	N 25°	Zenith Distance	S 50°
True Declination	S 15°	True Declination	N10°
Latitude	N 10°	Latitude	S 40°

2010. Longitude At Meridian Passage

Determining a vessel's longitude at LAN is straightforward. In the western hemisphere, the sun's GHA at LAN equals the vessel's longitude. In the eastern hemisphere, subtract the sun's GHA from 360° to determine longitude. The difficult part lies in determining the precise moment of meridian passage.

Determining the time of meridian passage presents a problem because the sun appears to hang for a finite time at its local maximum altitude. Therefore, noting the time of maximum sextant altitude is not sufficient for determining the precise time of LAN. Two methods are available to obtain LAN with a precision sufficient for determining longitude: (1) the graphical method and (2) the calculation method. The graphical method is discussed first below.

See Figure 2010. Approximately 30 minutes before the estimated time of LAN, measure and record sextant altitudes and their corresponding times. Continue taking sights for about 30 minutes after the sun has descended from the maximum recorded altitude. Increase the sighting frequency near the predicted meridian passage. One sight every 20-30 seconds should yield good results near meridian passage; less frequent sights are required before and after.

Plot the resulting data on a graph of sextant altitude versus time. Fair a curve through the plotted data. Next, draw a series of horizontal lines across the curve formed by the data points. These lines will intersect the faired curve at two different points. The x coordinates of the points where these lines intersect the faired curve represent the two different times when the sun's altitude was equal (one time when the sun was ascending; the other time when the sun was descending). Draw three such lines, and ensure the lines have sufficient vertical separation. For each line, average the two times where it intersects the faired curve. Finally, average the three resulting times to obtain a final value for the time of LAN. From the *Nautical Almanac*, determine the sun's GHA at that time; this is your longitude in the western hemisphere. In the eastern hemisphere, subtract the sun's GHA from 360° to determine longitude.

The second method of determining LAN is similar to the first. Estimate the time of LAN as discussed above, Measure and record the sun's altitude as the sun approaches its maximum altitude. As the sun begins to descend, set the sextant to correspond to the altitude recorded just before the sun's reaching its maximum altitude. Note the time when the sun is again at that altitude. Average the two times. Repeat this procedure with two other altitudes recorded before LAN, each time presetting the sextant to those altitudes and recording the corresponding times that the sun, now on its descent, passes through those altitudes. Average these corresponding times. Take a final average among the three averaged times; the result will be the time of meridian passage. Determine the vessel's longitude by determining the sun's GHA at the exact time of LAN.

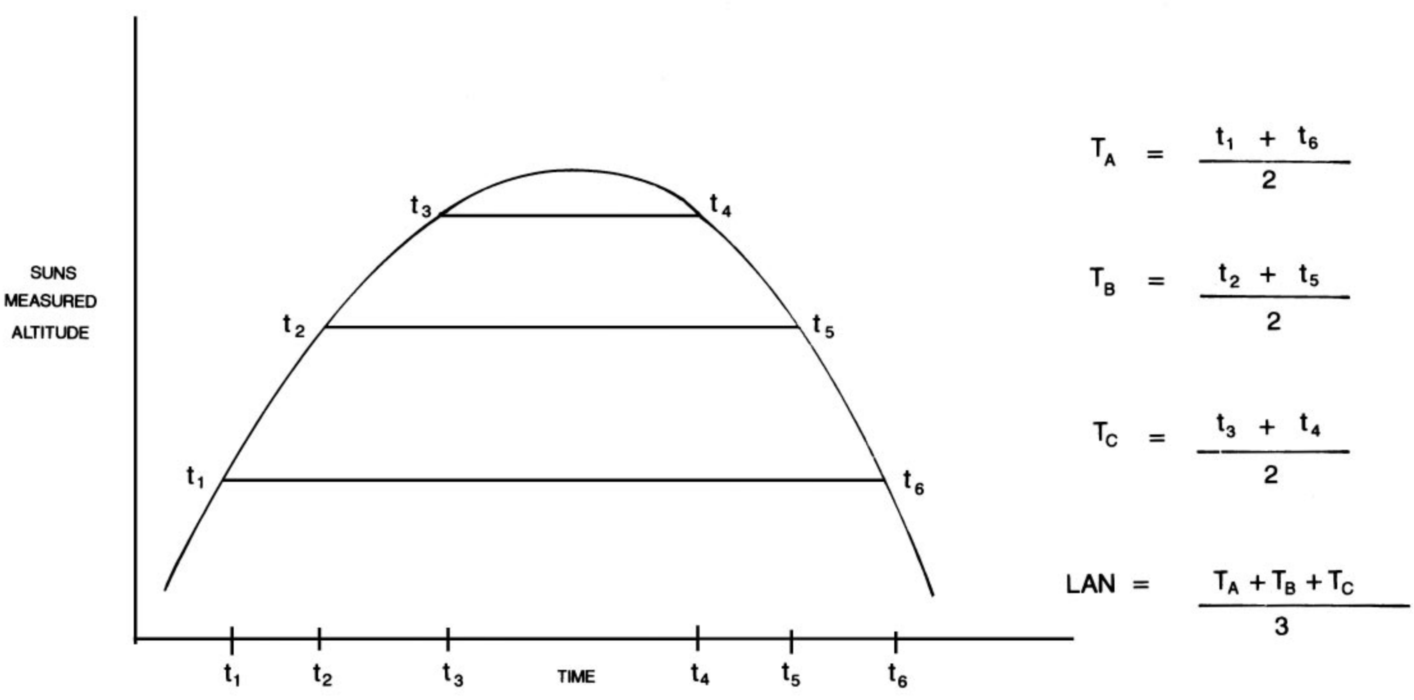


Figure 2010. Time of LAN.

LATITUDE BY POLARIS

2011. Latitude By Polaris

Since Polaris is always within about 1° of the North Pole, the altitude of Polaris, with a few minor corrections, equals the latitude of the observer. This relationship makes Polaris an extremely important navigational star in the northern hemisphere.

The corrections are necessary because Polaris orbits in a small circle around the pole. When Polaris is at the exact same altitude as the pole, the correction is zero. At two points in its orbit it is in a direct line with the observer and the pole, either nearer than or beyond the pole. At these points the corrections are maximum. The following example illustrates converting a Polaris sight to latitude.

At 23-18-56 GMT, on April 21, 1994, at DR λ=37° 14.0' W, L = 50° 23.8' N, the observed altitude of Polaris (h_o) is 49° 31.6'. Find the vessel's latitude.

To solve this problem, use the equation:

$$\text{Latitude} = h_o - 1° + A_0 + A_1 + A_2$$

where h_o is the sextant altitude (h_s) corrected as in any other star sight; 1° is a constant; and A_0, A_1, and A_2 are correction factors from the Polaris tables found in the *Nautical Almanac*. These three correction factors are always positive. One needs the following information to enter the tables: LHA of Aries, DR latitude, and the month of the year. Therefore:

Tabulated GHA ♈ (2300 hrs.)	194° 32.7'
Increment (18-56)	4° 44.8'
GHA ♈	199° 17.5'
DR Longitude (-W +E)	37° 14.0'
LHA ♈	162° 03.5'
A_0 (162° 03.5')	+1° 25.4'
A_1 (L = 50°N)	+0.6'
A_2 (April)	+0.9'
Sum	1° 26.9'
Constant	-1° 00.0'
Observed Altitude	49° 31.6'
Total Correction	+26.9'
Latitude	N 49° 58.5'

Enter the Polaris table with the calculated LHA of Aries (162° 03.5'). See Figure 2011. The first correction, A_0, is a function solely of the LHA of Aries. Enter the table column indicating the proper range of LHA of Aries; in this case, enter the 160°-169° column. The numbers on the left hand side of the A_0 correction table represent the whole degrees of LHA ♈ ; interpolate to determine the proper A_0 correction. In this case, LHA ♈ was 162° 03.5'. The A_0 correction for LHA = 162° is 1° 25.4' and the A_0 correction for LHA = 163° is 1° 26.1'. The A_0 correction for 162° 03.5' is 1° 25.4'.

To calculate the A_1 correction, enter the A_1 correction table with the DR latitude, being careful to stay in the 160°-169° LHA column. There is no need to interpolate here; simply choose the latitude that is closest to the vessel's DR latitude. In this case, L is 50°N. The A_1 correction corresponding to an LHA range of 160°-169° and a latitude of 50°N is + 0.6'.

Finally, to calculate the A_2 correction factor, stay in the 160°-169° LHA ♈ column and enter the A_2 correction table. Follow the column down to the month of the year; in this case, it is April. The correction for April is + 0.9'.

Sum the corrections, remembering that all three are always positive. Subtract 1° from the sum to determine the total correction; then apply the resulting value to the observed altitude of Polaris. This is the vessel's latitude.

POLARIS (POLE STAR) TABLES, 1994
FOR DETERMINING LATITUDE FROM SEXTANT ALTITUDE AND FOR AZIMUTH

LHA ARIES	120°– 129°	130°– 139°	140°– 149°	150°– 159°	160°– 169°	170°– 179°	180°– 189°	190°– 199°	200°– 209°	210°– 219°	220°– 229°	230°– 239°
	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0
°	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
0	0 53·9	1 01·8	1 09·7	1 17·2	1 24·1	1 30·3	1 35·5	1 39·6	1 42·5	1 44·1	1 44·3	1 43·2
1	54·7	02·6	10·4	17·9	24·8	30·9	36·0	40·0	42·7	44·2	44·3	43·0
2	55·5	03·4	11·2	18·6	25·4	31·4	36·4	40·3	42·9	44·3	44·2	42·8
3	56·3	04·2	12·0	19·3	26·1	32·0	36·9	40·6	43·1	44·3	44·1	42·6
4	57·1	05·0	12·7	20·0	26·7	32·5	37·3	40·9	43·3	44·4	44·0	42·4
5	0 57·8	1 05·8	1 13·5	1 20·7	1 27·3	1 33·0	1 37·7	1 41·2	1 43·5	1 44·4	1 43·9	1 42·1
6	58·6	06·6	14·2	21·4	27·9	33·5	38·1	41·5	43·6	44·4	43·8	41·9
7	0 59·4	07·3	15·0	22·1	28·5	34·1	38·5	41·8	43·8	44·4	43·7	41·6
8	1 00·2	08·1	15·7	22·8	29·1	34·6	38·9	42·0	43·9	44·4	43·5	41·3
9	01·0	08·9	16·4	23·5	29·7	35·0	39·3	42·3	44·0	44·4	43·4	41·0
10	1 01·8	1 09·7	1 17·2	1 24·1	1 30·3	1 35·5	1 39·6	1 42·5	1 44·1	1 44·3	1 43·2	1 40·7
Lat.	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1
°	′	′	′	′	′	′	′	′	′	′	′	′
0	0·2	0·2	0·3	0·3	0·4	0·4	0·5	0·6	0·6	0·6	0·6	0·6
10	·3	·3	·3	·4	·4	·5	·5	·6	·6	·6	·6	·6
20	·3	·4	·4	·4	·4	·5	·5	·6	·6	·6	·6	·6
30	·4	·4	·4	·5	·5	·5	·5	·6	·6	·6	·6	·6
40	0·5	0·5	0·5	0·5	0·5	0·6	0·6	0·6	0·6	0·6	0·6	0·6
45	·5	·5	·5	·6	·6	·6	·6	·6	·6	·6	·6	·6
50	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6
55	·7	·7	·7	·7	·6	·6	·6	·6	·6	·6	·6	·6
60	·8	·8	·7	·7	·7	·7	·6	·6	·6	·6	·6	·6
62	0·8	0·8	0·8	0·8	0·7	0·7	0·7	0·6	0·6	0·6	0·6	0·6
64	·9	·9	·8	·8	·8	·7	·7	·6	·6	·6	·6	·6
66	0·9	0·9	·9	·8	·8	·7	·7	·6	·6	·6	·6	·6
68	1·0	1·0	0·9	0·9	0·8	0·8	0·7	0·7	0·6	0·6	0·6	0·6
Month	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2
	′	′	′	′	′	′	′	′	′	′	′	′
Jan.	0·6	0·6	0·6	0·5	0·5	0·5	0·4	0·4	0·4	0·4	0·4	0·4
Feb.	·8	·8	·7	·7	·6	·6	·5	·5	·4	·4	·4	·3
Mar.	0·9	0·9	0·9	·8	·8	·7	·6	·6	·5	·5	·4	·4
Apr.	1·0	1·0	1·0	0·9	0·9	0·8	0·8	0·7	0·7	0·6	0·5	0·5
May	0·9	1·0	1·0	1·0	1·0	0·9	·9	·9	·8	·8	·7	·6
June	·8	0·9	0·9	0·9	0·9	1·0	·9	·9	·9	·9	·8	·8
July	0·7	0·7	0·8	0·8	0·8	0·9	0·9	0·9	0·9	0·9	0·9	0·9
Aug.	·5	·5	·6	·6	·7	·7	·8	·8	·8	·9	·9	·9
Sept.	·3	·4	·4	·5	·5	·6	·6	·7	·7	·7	·8	·8
Oct.	0·3	0·3	0·3	0·3	0·3	0·4	0·4	0·5	0·5	0·6	0·6	0·7
Nov.	·2	·2	·2	·2	·2	·2	·2	·3	·3	·4	·5	·5
Dec.	0·3	0·2	0·2	0·2	0·1	0·1	0·1	0·2	0·2	0·2	0·3	0·4
Lat.	AZIMUTH											
°	°	°	°	°	°	°	°	°	°	°	°	°
0	359·2	359·2	359·3	359·3	359·4	359·5	359·6	359·7	359·8	0·0	0·1	0·2
20	359·2	359·2	359·2	359·3	359·4	359·5	359·6	359·7	359·8	0·0	0·1	0·3
40	359·0	359·0	359·1	359·1	359·2	359·3	359·5	359·6	359·8	0·0	0·1	0·3
50	358·8	358·8	358·9	359·0	359·1	359·2	359·4	359·6	359·8	0·0	0·2	0·4
55	358·7	358·7	358·7	358·8	359·0	359·1	359·3	359·5	359·7	0·0	0·2	0·4
60	358·5	358·5	358·6	358·7	358·8	359·0	359·2	359·5	359·7	0·0	0·2	0·5
65	358·2	358·2	358·3	358·4	358·6	358·8	359·1	359·4	359·6	359·9	0·3	0·6

Figure 2011. Excerpt from the Polaris Tables.

CHAPTER 25

THE NAVIGATION PROCESS

INTRODUCTION

2500. Fundamentals

This chapter emphasizes the operational aspects of navigating in the open ocean. It is in this operational process that an individual navigator's experience and judgment become most crucial. Compounding this subject's difficulty is the fact that there are no set rules regarding the optimum employment of navigational systems and techniques. The navigation system's optimum use varies as a function of the type of vessel, the quality of the navigation equipment on board, and the experience and skill of the particular navigator.

For the watch officer, ensuring ship safety always takes priority over completing operational commitments and carrying out the ship's routine. This chapter discusses several basic safety considerations designed to minimize the probability of human error leading to a marine accident.

VOYAGE PLANNING

Voyage planning determines the safest and most efficient track for the ship to follow to ensure that the vessel completes its operational commitments. Constructing a planned track for a voyage is fundamentally important for ship's safety. The commanding officer and the navigator must carefully review and approve the track followed by the conning officer. Several ships' groundings have occurred because of unauthorized deviations from an approved track.

2501. Constructing A Voyage Plan Track

Construct the track using a navigation computer, a great circle (gnomonic) chart, or the sailings. This chapter will discuss only the navigation computer and the great circle chart. Chapter 24 covers the sailings. Use a navigation computer if one is available because the computer eliminates the plotting errors inherent in transferring the track from gnomonic to a Mercator projection.

When using a navigation computer, the navigator simply inputs the two endpoints of his planned voyage. The computer computes waypoints marking the great circle track between the two endpoints. The computer determines each track leg's distance and, given a speed of advance, calculates the times the vessel can expect to pass each waypoint. Construct the track on the Mercator chart by plotting the computer-generated waypoints and the tracks between them.

After adjusting the track as necessary to pass well clear of any hazard, choose a speed of advance (SOA) that ensures the ship will arrive on time at any required point. Given an SOA, mark the track with the ship's planned hourly positions. These planned positions are **points of intended movement (PIM's)**. The SOA chosen for each track leg is the **PIM speed**.

If a navigation computer is not available, use a gnomonic chart to plot a great circle route between points and to determine the position of resulting track points. Transfer these points to a Mercator chart as a succession of waypoints connected by rhumb lines. Figure 2501 illustrates this method. This figure shows a great circle route plotted as a straight line on a gnomonic chart and as a series of points when transferred to a Mercator chart. The arrows represent corresponding points on the two charts.

An operation order often assigns a naval vessel to an operating area. In that case, plan a track from the departure to the edge of the operating area to ensure that the vessel arrives at the operating area on time. Following a planned track inside the assigned area may be impossible because of the dynamic nature of a planned exercise. In that case, carefully examine the *entire* operating area for navigation hazards. If simply transiting through the area, the ship should still follow a planned and approved track.

2502. Following A Voyage Plan

Complete the planning discussed in section 2501 prior to leaving port. Once the ship is transiting, frequently compare the ship's actual position to the planned position and adjust the ship's course and speed to compensate for any deviations. Order courses and speeds to keep the vessel on track without significant deviation.

Often a vessel will have its operational commitments changed after it gets underway. If this happens, begin the voyage planning process anew. Ensure the ship's navigator and captain approve the new track corresponding to the new mission. The conning officer must understand that, unless transiting in an operating area as discussed above, he should never transit on a chart that does not have an approved track for him to follow.

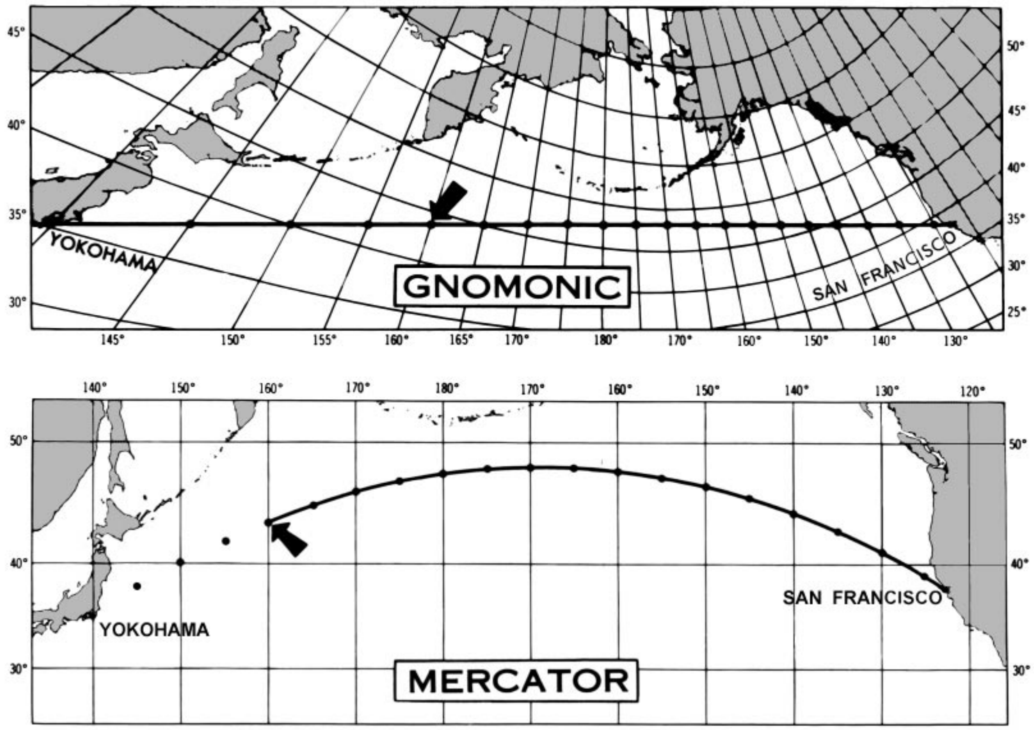


Figure 2501. Constructing a great circle track on a Mercator projection.

VOYAGE PREPARATION

2503. Equipment Inventory

Prior to getting the ship underway, inventory all navigation equipment, charts, and publications. The navigator should develop a checklist of navigation equipment specific to his vessel and check that all required equipment is onboard. The navigator should have all applicable Sailing Directions, pilot charts, and navigation charts covering his planned route. He should also have all charts and sailing direction covering ports at which his vessel may call. He should have all the equipment and publications required to support celestial navigation. Finally, he must have all technical documentation required to support the operation of his electronic navigation suite.

Complete this chart, publication, and equipment inventory well before the underway date and obtain all missing items before sailing.

2504. Chart Preparation

Just as the navigator must prepare charts for piloting, he must also prepare his charts for an open ocean transit. The following is a list of the minimum chart preparation required for an open ocean or coastal transit. Complete this preparation well before using the chart to maintain the plot.

Correcting The Chart: Correct all applicable charts through the latest *Notice to Mariners*, *Local Notice to Mariners*, and Broadcast Notice to Mariners. Ensure the chart to be used is the correct edition.

Plotting Approved Track: Section 2501 above discusses constructing the track. Mark the track course above the track line with a "C" followed by the course. Similarly, mark each track leg's distance under the course line with a "D" followed by the distance in nautical miles. Mark the PIM's at hourly intervals, and mark the time corresponding to each PIM.

Calculating Minimum Expected, Danger, And Warning Soundings: Chapter 8 discusses calculating minimum expected, danger and warning soundings. Determining these soundings is particularly important for ships passing a shoal close aboard. Set these soundings to warn the conning officer that he is passing too close to the shoal. Mark the minimum expected sounding, the warning sounding, and the danger sounding clearly on the chart and indicate the section

of the track for which they are applicable.

Marking Allowed Operating Areas: This chart preparation step is applicable to military vessels. Often an operation order assigns a naval vessel to an operating area for a specific period of time. There may be operational restrictions placed on the ship while within this area. For example, a surface ship assigned to an operating area may be ordered not to exceed a certain speed for the duration of an exercise. When assigned an operating area, clearly mark that area on the chart. Label it with the time the vessel must remain in the area and what, if any, operational restrictions it must follow. The conning officer and the captain should be able to glean the entire navigation situation from the chart alone without reference to the directive from which the chart was constructed. Therefore, put all operationally important information directly on the chart.

Marking Chart Shift Points: If the transit will require the ship to operate on more than one chart, mark the chart points where the navigator must shift to the next chart.

Examining 50nm On Either Side Of Track: Highlight any shoal water or other navigation hazard within 50nm of the planned track. This will alert the conning officer as he approaches a possible danger.

NAVIGATION ROUTINE AT SEA

2505. Frequency Of Position Determination

The table below lists recommended fix intervals as a function of navigation phase:

	Piloting	Coastal	Ocean
Frequency	3 min. or less	3-15 min.	30 min.

Shorten the suggested fix interval if required to ensure the vessel remains *at least two fix intervals from the nearest danger*. However, do not exceed the times recommended above. Choose a fix interval that provides a sufficient safety margin from all charted hazards.

Use all available fix information. With the advent of accurate satellite navigation systems, it is especially tempting to disregard this maxim. However, the experienced navigator never feels comfortable relying solely on one particular system. Supplement the satellite position with positions from Loran, celestial sights, radar lines of position, and visual observations. Evaluate the accuracy of the various fix methods against the satellite position; when the satellite receiver fails, the knowledge, for example, that Loran fixes consistently plotted 1 nm to the west of GPS can be helpful.

Use an inertial navigator if one is available. The inertial navigator may produce estimated positions more accurate than fix positions. Inertial navigators are completely independent of any external fix input. Therefore, they are invaluable for maintaining an accurate ship's position during periods when external fix sources are unavailable.

Always check a position determined by a fix, inertial navigator, or DR by comparing the charted sounding at the position with the fathometer reading. If the soundings do not correlate, investigate the discrepancy.

Chapter 7 covers the importance of maintaining a proper DR. It bears repeating here. Determine the difference between the fix and the DR positions at *every* fix and use this information to calculate an EP from every DR. Constant application of set and drift to the DR is crucial if the vessel must pass a known navigation hazard close aboard.

2506. Fathometer Operations

Use Figure 2506 to develop a standard procedure for operating the fathometer.

2507. The Modified Piloting Party

If operating out of piloting waters but near a navigation hazard, station a modified piloting party. As the name implies, this team does not consist of the entire piloting party. It could consist of only the navigator or assistant navigator, a plotter, and a recorder. Its purpose is to increase supervision of the navigation plot in areas that could pose a hazard to the vessel.

The navigator and captain should develop a standing order covering the stationing of a modified piloting party. A

Water Depth	Sounding Interval
Charted Water Depth < 100 ft.	Monitor fathometer continuously.
100 ft. < Charted Water Depth < 500 ft.	Take and record soundings every 15 minutes.
500 ft. < Charted Water Depth < 1000 ft.	Take and record soundings every 30 minutes.
Charted Water Depth > 1000 ft.	Take and record soundings every hour.

Figure 2506. Fathometer operating guidelines.

good rule is to station the modified piloting party when operating within 10 nm of a known hazard.

2508. Compass Checks

Determine gyro compass error at least daily as part of the at-sea routine. Check the gyro compass reading against the inertial navigator if the vessel has an inertial navigator. If the vessel does not have an inertial navigator, check gyro error using the celestial techniques discussed in Chapter 17. Report any error greater than 1° to the navigator and commanding officer.

Check the gyro repeaters and the magnetic compass against the gyro compass hourly and after each course change. When comparing the magnetic and gyro compasses, account for changes in variation and deviation. Report any repeater error greater than 1° to the commanding officer.

2509. Commanding Officer's Night Orders And Standing Orders

The Night Order book is the vehicle by which the captain informs the officer of the deck of the captain's orders for operating the ship. The Night Order book, despite its name, can contain orders for the entire 24 hour period after which the CO issues it.

The navigator may write the Night Orders pertaining to navigation. Such orders include assigned operating areas, maximum speeds allowed, required positions with respect to PIM, and, regarding submarines, the maximum depth at which the ship can operate. Each department head should include in the Night Order book the evolutions he wants to accomplish during the night that would normally require the captain's permission. The captain can add further orders and directions as required. When the captain signs the Night Order book, it becomes an official order to the Officer of the Deck.

The Officer of the Deck must not follow the Night Orders blindly. Circumstances under which the captain signed the Orders may have changed, rendering some evolutions ordered impractical to complete. The Officer of the Deck, when exercising his judgment on completing ordered evolutions, must always inform the captain of any deviation from the Night Orders as soon as such a deviation occurs.

The Commanding Officer's Night Orders are in effect only for the 24 hours after they are written; his Standing Orders are continuously in force. The captain sets the ship's navigation policy in these orders. He sets required fix intervals, intervals for fathometer operations, minimum CPA's, and other general navigation and collision avoidance requirements. The Officer of the Deck must follow the Commanding Officer's Standing Orders at all times. Report any deviation from these orders immediately to the Commanding Officer.

2510. Position Reports

If the captain requires position reports, deliver them at 0800, 1200, and 2000 each day. Prepare these reports approximately 30 minutes ahead of the time when they are due. Use the DR positions for the time of the report. For example, prepare the 2000 position report at 1930 using the ship's 2000 DR position. Often the captain will require additional information with these position reports. Some captains, for example, may want status reports on the engine room. Tailor each position report to contain the information the captain wants.

2511. Watch Relief Procedures

When a watch officer relieves as Officer of the Deck (OOD), he assumes the responsibility for the safe navigation of the ship. He becomes the Commanding Officer's direct representative in ensuring ship safety. As such, he must prepare himself fully prior to assuming the watch. The following list contains those items that, as a minimum, the relieving OOD must check prior to assuming the watch.

- **Conduct a Pre Watch Tour:** The relieving OOD should tour the ship prior to his watch. He should familiarize himself with any maintenance in progress. He should check for general cleanliness and stowage. He should order any loose gear that could pose a safety hazard in rough seas secured.

- **Check the Position Log and Chart:** Check the type and accuracy of the ship's last fix. Verify that the navigation watch has plotted the last fix properly. Ensure there is a properly constructed DR plot on the chart. Examine the DR for any potential navigation hazards. Check ship's position with respect to the PIM. Ensure that the ship is in the correct operating area, if applicable. Check to ensure that the navigation watch has properly applied fix expansion in accordance with the navigator's instructions.

- **Check the Fathometer Log:** Ensure that previous watches have taken soundings at required intervals and that the navigation watch took a sounding at the last fix. Verify that the present sounding matches the charted sounding at the vessel's charted position.

- **Check the Compass Record Log:** Verify that the navigation watch has conducted compass checks at the proper interval. Verify that gyro error is less than 1° and that all repeaters agree within 1° with the master gyro.

- **Read the Commanding Officer Night Orders:** Check the Night Order Book for the captain's directions for the duration of the watch.

- **Check Planned Operations:** For any planned operations, verify that the ship has met all operational prerequisites, that the ship is in the correct operating

area, and that all watchstanders have reviewed the operation order. If the operation is a complicated one, consider holding an operations brief with applicable watchstanders prior to assuming the watch.

- **Check the Broadcast Schedule:** Read any message traffic that could have a bearing on the upcoming watch. If the ship is on a broadcast schedule, find out when the radio operator received the last broadcast (military vessels only). Determine if the radio operator has any messages to transmit during the watch.

- **Ascertain the Contact Situation:** Check the radar and sonar contact picture, if so equipped. Determine which contact has the closest CPA and what maneuvers, if any, will be required to open CPA. Find out from the offgoing OOD if there have been any bridge-to-bridge communications with any vessels in the area. Check that no CPA will be less than the minimum set by the Commanding Officer's Standing Orders.

- **Review Watchstander Logs:** Review the log readings for all watchstanders. Note any out of specification readings or any trends in log readings indicating that a parameter will soon go out of specification.

After conducting the above listed checks, the relieving OOD should report to the on watch OOD that he is ready to relieve the watch. The on watch OOD then should brief the relieving OOD on the following:

- Vessel's present course and speed.
- Vessel's present depth (submarines only).
- Any evolutions planned or in progress.
- The status of the engineering plant.
- The status of repair on any out of commission equipment that effects the ship's operational capability.
- Any orders from the Commanding Officer not expressly given in the Night Orders.
- Status of cargo (merchant vessels only).
- Any hazardous maintenance planned or in progress.
- Any routine maintenance planned or in progress.
- Any planned ship's drills.

If the relieving OOD has no questions following this brief, then he should relieve the watch. Upon relieving the watch, he should announce to both the helmsman and the quartermaster that he has the deck and the conn. The quartermaster should log the change of watch in the ship's deck log.

Watch officers should not relieve the watch in the middle of an evolution or when casualty procedures are being carried out. Relieve the watch only during a steady state operational and tactical situation. This ensures that there is watchstander continuity when carrying out a specific evolution or combating a casualty.

THE DAY'S WORK IN CELESTIAL NAVIGATION

The advent of accurate electronic and satellite navigation systems has relegated celestial navigation to use solely as a backup navigation method. Seldom if ever will a ship undertake an ocean transit relying only on celestial navigation. Therefore, the navigator need not follow the entire routine listed below if celestial navigation is not his primary navigation source. Use only the steps of the celestial day's work that are necessary to provide a meaningful check on the primary fix source's accuracy. Should the electronic navigation system fail, however, and should celestial navigation become the primary means of navigation, this section provides a comprehensive procedure to follow.

2512. Celestial Navigation Routine

Complete a typical day's work in open celestial navigation as follows:

1. Plot the dead reckoning position.
2. Reduce celestial observations for a fix during morning twilight.
3. Wind the chronometer and determine chronometer error.
4. Reduce a sun sight for a morning sun line.
5. Calculate an azimuth of the sun for a compass check. The navigator normally obtains an azimuth at about the same time as he takes a morning sun observation. He may also check the compass with an amplitude observation at sunrise.
6. Observe the sun at local apparent noon. Cross the resulting LOP with an advanced morning sun line or with a longitude determined at LAN for a fix or running fix.
7. Reduce a sun sight during the afternoon. This is primarily for use with an advanced noon sun line, or with a moon or Venus line, if the skies are overcast during evening twilight.
8. Calculate an azimuth of the sun for a compass check at about the same time as the afternoon sun observation. The navigator may replace this azimuth with an amplitude observation at sunset.
9. Reduce celestial observations for a fix during evening twilight.

Chapter 7, Chapter 17, and Chapter 20 contain detailed explanations of the procedures required to carry out this routine.

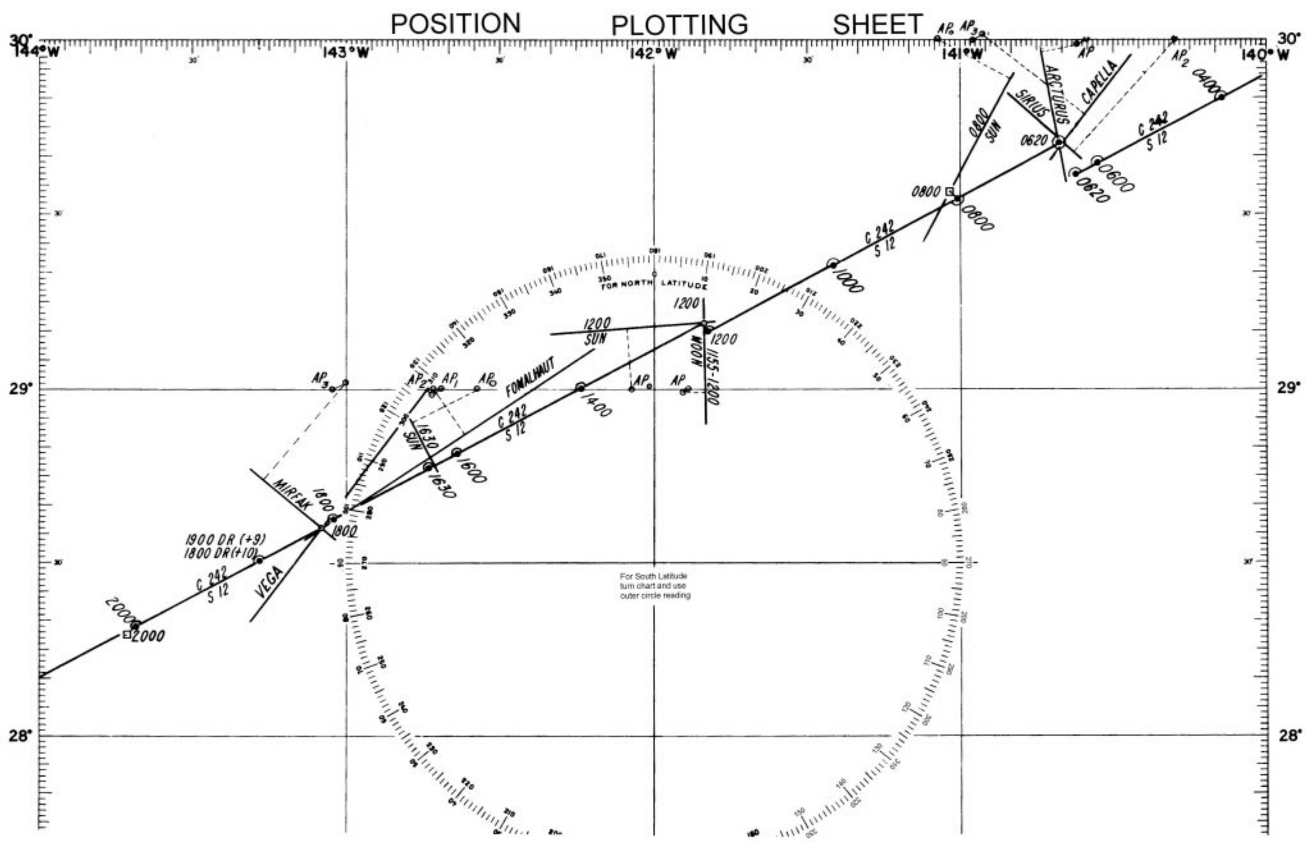


Figure 2512. Typical celestial plot at sea.

SPECIAL CONSIDERATIONS FOR SMALL CRAFT

2513. Navigation Of Small Craft

In principle, the navigation of small craft is the same as that of larger vessels. However, because of a small craft's shallower draft, greater maneuverability, and possible limitations of equipment and expertise, there are important differences. Small craft often spend most of their time within sight of land, and their navigation is largely a matter of piloting. They generally are close enough inshore to reach safety in case of storm or fog. Since most of them are primarily pleasure craft, there is a tendency for their navigation to be a less professional process than in commercial or military craft.

Regardless of the nature of the craft, it should carry the minimum safety equipment required by the U.S. Coast Guard. In addition to this Coast Guard mandated safety equipment, a small craft should also carry a compass, charts, plotting devices, speed log, tide tables, Coast Pilot or Sailing Directions, and binoculars.

All craft venturing offshore should carry a properly registered EPIRB and VHF radio. Loran C, Omega, and GPS receivers are available; boats that transit out of sight of land should have at least one of these.

If the craft is to proceed out of sight of land for more than short intervals, celestial navigation equipment should be aboard. This equipment should include a sextant, an accurate timepiece, a means of receiving time signals, an almanac, and sight reduction tables. Celestial navigation calculators or computer programs are also useful.

A small craft navigator of limited experience may underestimate the importance of professional navigation. However, his vessel's safety depends on his skill. He must plan his track and know his position at all times. Small craft navigation also requires a complete, accurate, and neat plot. Where this is impractical because of heavy weather or limited plotting space, use a careful log and dead reckoning plot.

CONCLUSION

2514. The Importance Of The Navigation Process

Navigating a vessel is a dynamic process. Schedules change; missions change. Planning a voyage is a process that begins well before the ship gets underway. Executing that plan does not end until the ship ties up at the pier at its final destination.

Develop a navigation process encompassing the principles discussed in this chapter. Carefully planning a route, preparing required charts, and closely monitoring the ship's position enroute are fundamental concepts of safe navigation. A mariner should never feel comfortable unless he is following an approved track plotted on a corrected chart on which he has frequently updated his position.

Developing and implementing such a routine is only half of the battle. Watchstanders must follow approved procedures. U.S. Navy grounding reports and U.S. Coast Guard accident reports attest to the danger courted when a vessel disregards basic navigation safety.

CHAPTER 26

EMERGENCY NAVIGATION

INTRODUCTION

2600. Planning For Emergency Navigation

With a complete set of emergency equipment, emergency navigation differs little from traditional shipboard navigation routine. Increasing reliance on complex electronic systems has changed the perspective of emergency navigation. Today it is more likely that a navigator will suffer failure of electronic devices and be left with little more than a sextant with which to navigate than that he will be forced to navigate a lifeboat. In the event of failure or destruction of electronic systems, navigational equipment and methods may need to be improvised. The officer who regularly navigates by blindly "filling in the blanks" or reading the coordinates from "black boxes" will not be prepared to use basic principles to improvise solutions in an emergency.

For offshore voyaging, the professional navigator must become thoroughly familiar with the theory of celestial navigation. He should be able to identify the most useful stars and know how to solve his sights by any widely used method. He should be able to construct a plotting sheet with a protractor and improvise a sextant. For the navigator prepared with such knowledge the situation is never hopeless. Some method of navigation is *always* available. This was recently proven by a sailor who circumnavigated the earth using no instruments of any kind, not even a compass. Basic knowledge can suffice.

The modern ship's regular navigation gear consists of many complex electronic systems. Though they may posses a limited backup power supply, most depend on an uninterrupted supply of electrical power. The failure of that power due to hostile action, fire, or breakdown can instantly render the unprepared navigator helpless. This discussion is intended to provide the navigator with the information needed to navigate a vessel in the absence of the regular suite of navigation gear. Training and preparation for a navigation emergency are essential. This should consist of regular practice in the techniques discussed herein while the regular navigation routine is in effect, so that confidence in emergency procedures is established.

BASIC TECHNIQUES OF EMERGENCY NAVIGATION

2601. Emergency Navigation Kit

The navigator should assemble a kit containing equipment for emergency navigation. Even with no expectation of danger, it is good practice to have such a kit permanently located in the chart room or on the bridge so that it can be quickly broken out if needed. It can be used on the bridge in the event of destruction or failure of regular navigation systems, or taken to a lifeboat if the "abandon ship" call is made.

If practical, full navigational equipment should be provided in the emergency kit. As many as possible of the items in the following list should be included.

1. A **notebook** or journal suitable for use as a deck log and for performing computations.
2. **Charts and plotting sheets**. A pilot chart is excellent for emergency use. It can be used for plotting and as a source of information on compass variation, shipping lanes, currents, winds, and weather. Charts for both summer and winter seasons should be included. Plotting sheets are useful but not essential if charts are available. Universal plotting sheets may be preferred, particularly if the latitude coverage is large. Include maneuvering boards and graph paper.
3. **Plotting equipment**. Pencils, erasers, a straightedge, protractor or plotter, dividers and compasses, and a knife or pencil sharpener should be included. A ruler is also useful.
4. **Timepiece**. A good watch is needed if longitude is to be determined astronomically. It should be waterproof or kept in a waterproof container which permits reading and winding of the watch if necessary without exposing it to the elements. The optimum timepiece is a quartz crystal chronometer, but any high-quality digital wristwatch will suffice if it is synchronized with the ship's chronometer. A portable radio capable of receiving time signals, together with a good wristwatch, will also suffice.
5. **Sextant**. A marine sextant should be included. If this is impractical, an inexpensive plastic sextant will suf-

fice. Several types are available commercially. The emergency sextant should be used periodically in actual daily navigation so its limitations and capabilities are fully understood. Plastic sextants have been used safely on extensive ocean voyages. Do not hesitate to use them in an emergency.

6. **Almanac**. A current *Nautical Almanac* contains ephemeral data and concise sight reduction tables. Another year's almanac can be used for stars and the sun without serious error by emergency standards. Some form of long-term almanac might be copied or pasted in the notebook.
7. **Tables**. Some form of table will be needed for reducing celestial observations. The *Nautical Almanac* produced by the U. S. Naval Observatory contains detailed procedures for calculator sight reduction and a compact sight reduction table.
8. **Compass**. Each lifeboat must carry a magnetic compass. For shipboard use, make a deviation table for each compass with magnetic material in its normal place. The accuracy of each table should be checked periodically.
9. **Flashlight**. A flashlight is required in each lifeboat. Check the batteries periodically and include extra batteries and bulbs in the kit.
10. **Portable radio**. A transmitting-receiving set approved by the Federal Communications Commission for emergency use can establish communications with rescue authorities. A small portable radio may be used as a radio direction finder or for receiving time signals.
11. An **Emergency Position Indicating Radiobeacon (EPIRB)** is *essential*. When activated, this device emits a signal which will be picked up by the COSPAS/SARSAT satellite system and automatically relayed to a ground station. It is then routed directly to rescue authorities. The location of the distress can be determined very accurately. Depending on the type of EPIRB, the signal may even identify the individual vessel in distress, thus allowing rescuers to determine how many people are in danger, the type of emergency gear they may have, and other facts to aid in the rescue. Because of this system, the navigator must question the wisdom of navigating away from the scene of the distress. It may well be easier for rescue forces to find him if he remains in one place. See Chapter 28, The Global Maritime Distress and Safety System (GMDSS).

2602. Most Probable Position

In the event of failure of primary electronic navigation systems, the navigator may need to establish the **most probable position** (MPP) of the vessel. Usually there is usually little doubt as to the position. The most recent fix updated with a DR position will be adequate. But when conflicting information or information of questionable reliability is received, the navigator must determine an MPP.

When complete positional information is lacking, or when the available information is questionable, the most probable position might be determined from the intersection of a single line of position and a DR, from a line of soundings, from lines of position which are somewhat inconsistent, or from a dead reckoning position with a correction for current or wind. Continue a dead reckoning plot from one fix to another because the DR plot often provides the best estimate of the MPP.

A series of estimated positions may not be consistent because of the continual revision of the estimate as additional information is received. However, it is good practice to plot all MPP's, and sometimes to maintain a separate EP plot based upon the best estimate of track and speed made good over the ground. This could indicate whether the present course is a safe one. See Chapter 23.

2603. Plotting Sheets

If plotting sheets are not available, a Mercator plotting sheet can be constructed through either of two alternative methods based upon a graphical solution of the secant of the latitude, which approximates the expansion of latitude.

First method (Figure 2603a):

Step one. Draw a series of equally spaced vertical lines at any spacing desired. These are the meridians; label them at any desired interval, such as 1', 2', 5', 10', 30', 1°, etc.

Step two. Draw and label a horizontal line through the center of the sheet to represent the parallel of the mid-latitude of the area.

Step three. Through any convenient point, such as the intersection of the central meridian and the parallel of the mid-latitude, draw a line making an angle with the horizontal equal to the mid-latitude. In Figure 2603a this angle is 35°.

Step four. Draw in and label additional parallels. The length of the oblique line between meridians is the perpendicular distance between parallels, as shown by the broken arc. The number of minutes of arc between parallels is the same as that between the meridians.

Step five. Graduate the oblique line into convenient units. If 1' is selected, this scale serves as both a latitude and mile scale. It can also be used as a longitude scale by measuring horizontally from a meridian instead of obliquely along the line.

The meridians may be shown at the desired interval and

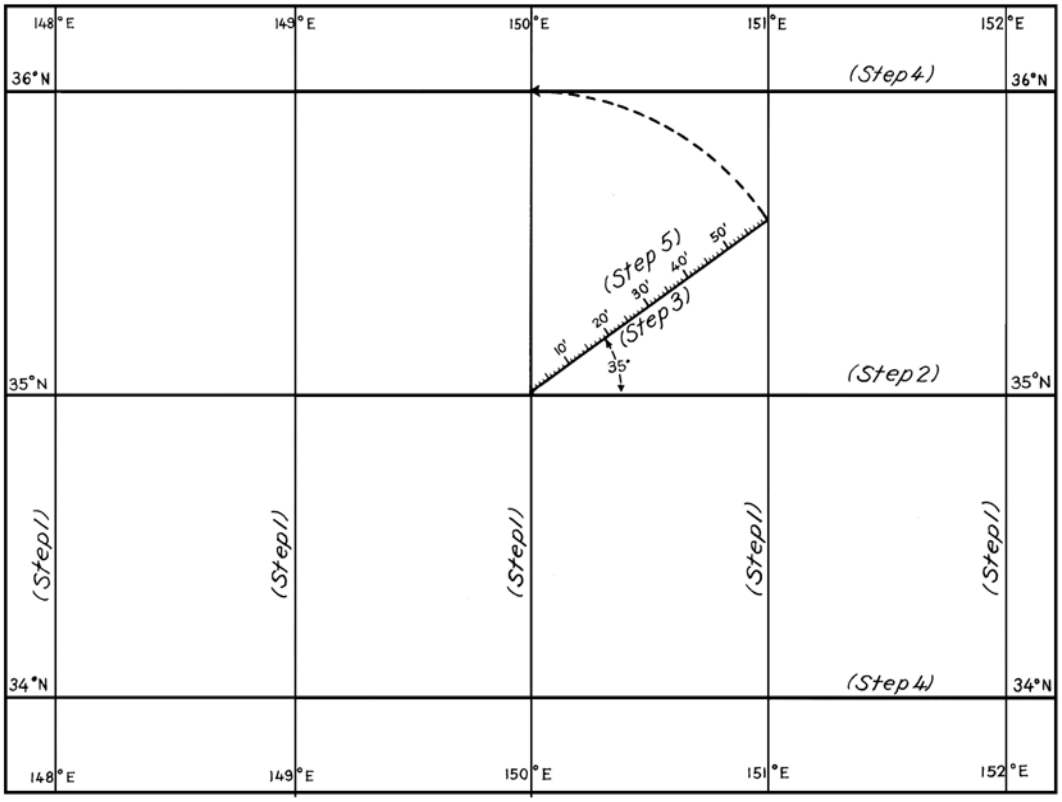


Figure 2603a. Small area plotting sheet with selected longitude scale.

the mid-parallel may be printed and graduated in units of longitude. In using the sheet it is necessary only to label the meridians and draw the oblique line. From it determine the interval used to draw in and label additional parallels. If the central meridian is graduated, the oblique line need not be.

Second method (Figure 2603b).

Step one. At the center of the sheet draw a circle with a radius equal to 1° (or any other convenient unit) of latitude at the desired scale. If a sheet with a compass rose is available, as in Figure 2603b, the compass rose can be used as the circle and will prove useful for measuring directions. It need not limit the scale of the chart, as an additional concentric circle can be drawn, and desired graduations extended to it.

Step two. Draw horizontal lines through the center of the circle and tangent at the top and bottom. These are parallels of latitude; label them accordingly, at the selected interval (as every 1°, 30', etc.).

Step three. From the center of the circle draw a line making an angle with the horizontal equal to the mid-latitude. In Figure 2603b this angle is 40°.

Step four. Draw in and label the meridians. The first is a vertical line through the center of the circle. The second is a vertical line through the intersection of the oblique line and the circle. Additional meridians are drawn the same distance apart as the first two.

Step five. Graduate the oblique line into convenient units. If 1' is selected, this scale serves as a latitude and mile scale. It can also be used as a longitude scale by measuring horizontally from a meridian, instead of obliquely along the line.

In the second method, the parallels may be shown at the desired interval, and the central meridian may be printed and graduated in units of latitude. In using the sheet it is necessary only to label the parallels, draw the oblique line, and from it determine the interval and draw in and label additional meridians. If the central meridian is graduated, as shown in Figure 2603b, the oblique line need not be.

The same result is produced by either method. The first method, starting with the selection of the longitude scale, is particularly useful when the longitude limits of the plotting sheet determine the scale. When the latitude coverage is more important, the second method may be preferable. In either method a central compass rose might be printed.

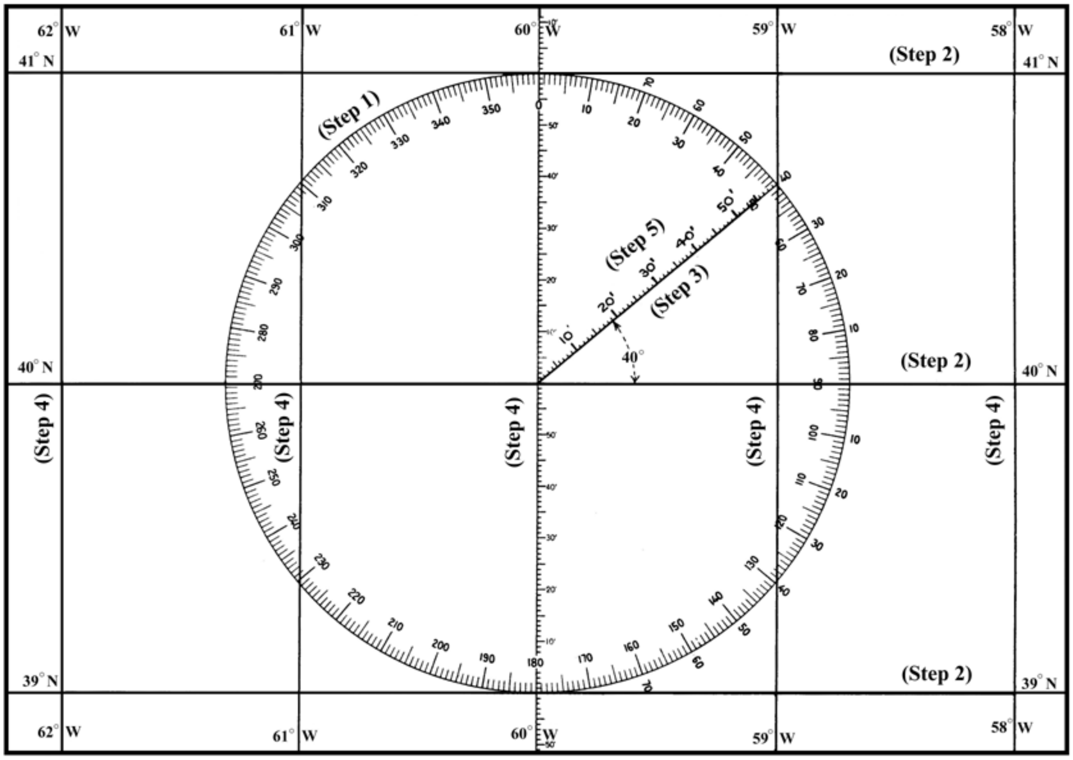


Figure 2603b. Small area plotting sheet with selected latitude scale.

Both methods use a constant relationship of latitude to longitude over the entire sheet and both fail to allow for the ellipticity of the earth. For practical navigation these are not important considerations.

2604. Dead Reckoning

Of the various types of navigation, dead reckoning alone is always available in some form. In an emergency it is of more than average importance. With electronic systems out of service, keep a close check on speed, direction, and distance made good. Carefully evaluate the effects of wind and current. Long voyages with accurate landfalls have been successfully completed by this method alone. This is not meant to minimize the importance of other methods of determining position. However, dead reckoning positions may be more accurate than those determined by other methods. If the means of determining direction and distance (the elements of dead reckoning) are accurate, it may be best to adjust the dead reckoning only after a confirmed fix.

Plotting can be done directly on a pilot chart or plotting sheet. If this proves too difficult, or if an independent check is desired, some form of mathematical reckoning may be useful. Table 2604, a simplified traverse table, can be used for this purpose. This is a critical-type table, various factors being given for limiting values of certain angles. To find the difference or change of latitude in minutes, enter the table with course angle, reckoned from north or south toward the east or west. Multiply the distance run, in miles, by the factor. To find the departure in miles, enter the table with the complement of the course angle. Multiply the distance run in miles by the factor. To convert departure to difference of longitude in minutes, enter the table with mid-latitude and divide the departure by the factor.

Example: *A vessel travels 26 miles on course 205°, from Lat. 41°44'N, Long. 56°21'W.*

Required: *Latitude and longitude of the point of arrival.*

Solution: *The course angle is 205° - 180° = S25°W, and the complement is 90° - 25° = 65°. The factors corresponding to these angles are 0.9 and 0.4, respectively. The difference of latitude is 26×0.9 = 23' (to the nearest minute) and the depar-*

Angle	0		18		31		41		49		56		63		69		75		81		87		90
Factor		1.0		0.9		0.8		0.7		0.6		0.5		0.4		0.3		0.2		0.1		0.0	

Table 2604. Simplified traverse table.

ture is 26 × 0.4 = 10 mi. Since the course is in the southwestern quadrant, in the Northern Hemisphere, the latitude of the point of arrival is 41°44' N -23' = 41°21'N. The factor corresponding to the mid-latitude 41°32'N is 0.7. The difference of longitude is 10 ÷ 0.7 = 14'. The longitude of the point of arrival is 56°21'W + 14 = 56°35'W.

Answer: *Lat. 41°21'N, Long. 56°35'W.*

2605. Deck Log

At the beginning of a navigation emergency a navigation log should be started. The date and time of the casualty should be the first entry, followed by navigational information such as ship's position, status of all navigation systems, the decisions made, and the reasons for them.

The best determination of the position of the casualty should be recorded, followed by a full account of courses, distances, positions, winds, currents, and leeway. No important navigational information should be left to memory if it can be recorded.

2606. Direction

Direction is one of the elements of dead reckoning. A deviation table for each compass, including lifeboat compasses, should already have been determined. In the event of destruction or failure of the gyrocompass and bridge magnetic compass, lifeboat compasses can be used.

If an almanac, accurate Greenwich time, and the necessary tables are available, the azimuth of any celestial body can be computed and this value compared with an azimuth measured by the compass. If it is difficult to observe the compass azimuth, select a body dead ahead and note the compass heading. The difference between the computed and observed azimuths is compass error on that heading. This is of more immediate value than deviation, but if the latter is desired, it can be determined by applying variation to the compass error.

Several unique astronomical situations occur, permitting determination of azimuth without computation:

Polaris: Polaris is always within 2° of true north for observers between the equator and latitude 60°N. When this star is directly above or below the celestial pole, its azimuth is exactly north at any latitude. This occurs approximately when the trailing star of either Cassiopeia or the Big Dipper (Alkaid) is directly above or directly below Polaris (Figure 2611). When a line through the trailing stars and Polaris is horizontal, the maximum correction should be applied. Below latitude 50° this can be considered 1°; and between 50° and 65°, 2°. If Cassiopeia is to the right of Polaris, the azimuth is 001° (or 002°), and if to the left, 359° (or 358°). The south celestial pole is located approximately at the intersection of a line through the longer axis of the Southern Cross with a line from the northernmost star of Triangulum Australe perpendicular to the line joining the other two stars of the triangle. No conspicuous star marks this spot (See star charts in Chapter 15).

Meridian transit: Any celestial body bears due north or south at meridian transit, either upper or lower. This is the moment of maximum (or minimum) altitude of the body. However, since the altitude at this time is nearly constant during a considerable change of azimuth, the instant of meridian transit may be difficult to determine. If time and an almanac are available, and the longitude is known, the time of transit can be computed. It can also be graphed as a curve on graph paper and the time of meridian transit determined with sufficient accuracy for emergency purposes.

Body on prime vertical: If any method is available for determining when a body is on the prime vertical (due east or west), the compass azimuth at this time can be observed. Table 20, Meridian Angle and Altitude of a Body on the Prime Vertical Circle provides this information. Any body on the celestial equator (declination 0°) is on the prime vertical at the time of rising or setting. For the sun this occurs at the time of the equinoxes. The star Mintaka (δ Orionis), the leading star of Orion's belt, has a declination of approximately 0.3°S and can be considered on the celestial equator. For an observer near the equator, such a body is always nearly east or west. Because of refraction and dip, the azimuth should be noted when the center of the sun or a star is a little more than one sun diameter (half a degree) above the horizon. The moon should be observed when its upper limb is on the horizon.

Body at rising or setting: Except for the moon, the azimuth angle of a body is almost the same at rising as at setting, except that the former is toward the east and the latter toward the west. If the azimuth is measured both at rising and setting, true south (or north) is midway between the two observed values, and the difference between this value and 180° (or 000°) is the compass error. Thus, if the compass azimuth of a body is 073° at rising, and 277° at setting, true south (180°) is $\frac{073° + 277°}{2} = 175$ by compass, and the compass error is 5°E. This method may be in error if the vessel is moving rapidly in a north or south direction. If the declination and latitude are known, the true azimuth of any body at rising or setting can be determined by means of a diagram on the plane of the celestial meridian or by computation. For this purpose, the body (except the moon) should be considered as rising or setting when its center is a little more than one sun diameter (half a degree) above the horizon, because of refraction and dip.

Finding direction by the relationship of the sun to the hands of a watch is sometimes advocated, but the limitations of this method prevent its practical use at sea.

A simple technique can be used for determining deviation. An object that will float but not drift rapidly before the wind is thrown overboard. The vessel is then steered steadily in the opposite direction to that desired. At a distance of perhaps half a mile, or more if the floating object is still clearly in view, the vessel is turned around in the smallest practical radius, and headed back toward the floating object. The magnetic course is midway between the course toward the object and the reciprocal of the course away from the ob-

ject. Thus, if the boat is on compass course 151° while heading away from the object, and 337° while returning, the magnetic course is midway between 337° and 151° + 180°

$$= 331°\text{ , or } \frac{337 + 331}{2} = 334°\text{ .}$$

Since 334° magnetic is the same as 337° by compass, the deviation on this heading is 3°W.

If a compass is not available, any celestial body can be used to steer by, if its diurnal apparent motion is considered. A reasonably straight course can be steered by noting the direction of the wind, the movement of the clouds, the direction of the waves, or by watching the wake of the vessel. The angle between the centerline and the wake is an indication of the amount of leeway.

A body having a declination the same as the latitude of the destination is directly over the destination once each day, when its hour angle equals the longitude, measured westward through 360°. At this time it should be dead ahead if the vessel is following the great circle leading directly to the destination. The *Nautical Almanac* can be inspected to find a body with a suitable declination.

EMERGENCY CELESTIAL NAVIGATION

2607. Almanacs

Almanac information, particularly declination and Greenwich hour angle of bodies, is important to celestial navigation. If the current *Nautical Almanac* is available, there is no problem. If the only copy available is for a previous year, it can be used for the sun, Aries, and stars without serious error, by emergency standards. However, for greater accuracy, proceed as follows:

For declination of the sun, enter the almanac with a time that is earlier than the correct time by $5^h 49^m$ times the number of years between the date of the almanac and the correct date, adding 24 hours for each February 29 that occurs between the dates. If the date is February 29, use March 1 and reduce by one the number of 24 hour periods added. For GHA of the sun or Aries, determine the value for the correct time, adjusting the minutes and tenths of arc to agree with that at the time for which the declination is determined. Since the adjustment never exceeds half a degree, care should be used when the value is near a whole degree, to prevent the value from being in error by 1°.

If no almanac is available, a rough approximation of the declination of the sun can be obtained as follows: Count the days from the given date to the nearer solstice (June 21 or December 22). Divide this by the number of days from that solstice to the equinox (March 21 or September 23), using the equinox that will result in the given date being between it and the solstice. Multiply the result by 90°. Enter Table 2604 with the angle so found and extract the factor. Multiply this by 23.45° to find the declination.

Example 1: *The date is August 24.*

Required: *The approximate declination of the sun.*

Solution: *The number of days from the given date to the nearer solstice (June 21) is 64. There are 94 days between June 21 and September 23. Dividing and multiplying by 90°,*

$$\frac{64}{94} \times 90° = 61.3'$$

The factor from Table 2604 is 0.5. The declination is 23.45° × 0.5 = 11.7°. We know it is north because of the date.

Answer: *Dec. 11.7°N.*

The accuracy of this solution can be improved by considering the factor of Table 2604 as the value for the midangle between the two limiting ones (except that 1.00 is correct for 0° and 0.00 is correct for 90°), and interpolating to one additional decimal. In this instance the interpolation would be between 0.50 at 59.5 and 0.40 at 66°. The interpolated value is 0.47, giving a declination of 11.0°N. Still greater accuracy can be obtained by using a table of natural cosines instead of Table 2604. By natural cosine the value is 11.3°N.

If the latitude is known, the declination of any body can be determined by observing a meridian altitude. It is usually best to make a number of observations shortly before and after transit, plot the values on graph paper, letting the ordinate (vertical scale) represent altitude, and the abscissa (horizontal scale) the time. The altitude is found by fairing a curve or drawing an arc of a circle through the points, and taking the highest value. A meridian altitude problem is then solved in reverse.

Example 2: *The latitude of a vessel is 40°16'S. The sun is observed on the meridian, bearing north. The observed altitude is 36°29'.*

Required: *Declination of the sun.*

Solution: *The zenith distance is 90° - 36°29' = 53°31'. The sun is 53°31' north of the observer, or 13°15' north of the equator. Hence, the declination is 13°15' N.*

Answer: *Dec. 13°15' N.*

The GHA of Aries can be determined approximately by considering it equal to GMT (in angular units) on September 23. To find GHA Aries on any other date, add 1° for each day following September 23. The value is ap-

proximately 90° on December 22, 180° on March 21, and 270° on June 21. The values so found can be in error by as much as several degrees, and so should not be used if better information is available. An approximate check is provided by the great circle through Polaris, Caph (the leading star of Cassiopeia), and the eastern side of the square of Pegasus. When this great circle coincides with the meridian, LHA ♈ is approximately 0°. The hour angle of a body is equal to its SHA plus the hour angle of Aries.

If an error of up to 4°, or a little more, is acceptable, the GHA of the sun can be considered equal to GMT ± 180° (12^h). For more accurate results, one can make a table of the equation of time from the Nautical Almanac perhaps at five- or ten-day intervals, and include this in the emergency navigation kit. The equation of time is applied according to its sign to GMT ± 180° to find GHA.

2608. Altitude Measurement

With a sextant, altitudes are measured in the usual manner. If in a small boat or lifeboat, it is a good idea to make a number of observations and average both the altitudes and times, or plot on graph paper the altitudes versus time. The rougher the sea, the more important is this process, which tends to average out errors caused by heavy weather observations.

The improvisations which may be made in the absence of a sextant are so varied that in virtually any circumstances a little ingenuity will produce a device to measure altitude. The results obtained with any improvised method will be approximate at best, but if a number of observations are averaged, the accuracy can be improved. A measurement, however approximate, is better than an estimate. Two general types of improvisation are available:

1. Circle. Any circular degree scale, such as a maneuvering board, compass rose, protractor, or plotter can be used to measure altitude or zenith distance directly. This is the principle of the ancient astrolabe. A maneuvering board or compass rose can be mounted on a flat board. A protractor or plotter may be used directly. There are a number of variations of the technique of using such a device. Some of them are:

A peg or nail is placed at the center of the circle. A weight is hung from the 90° graduation, and a string for holding the device is attached at the 270° graduation. When it is held with the weight acting as a plumb bob, the 0° - 180° line is horizontal. In this position the board is turned in azimuth until it is in line with the sun. The intersection of the shadow of the center peg with the arc of the circle indicates the altitude of the center of the sun.

The weight and loop can be omitted and pegs placed at the 0° and 180° points of the circle. While one observer sights along the line of pegs to the horizon, an assistant notes the altitude.

The weight can be attached to the center pin, and the three pins (0°, center, 180°) aligned with the celestial body. The reading is made at the point where the string holding the weight crosses the scale. The reading thus obtained is the zenith distance unless the graduations are labeled to indicate altitude. This method, illustrated in Figure 2608b, is

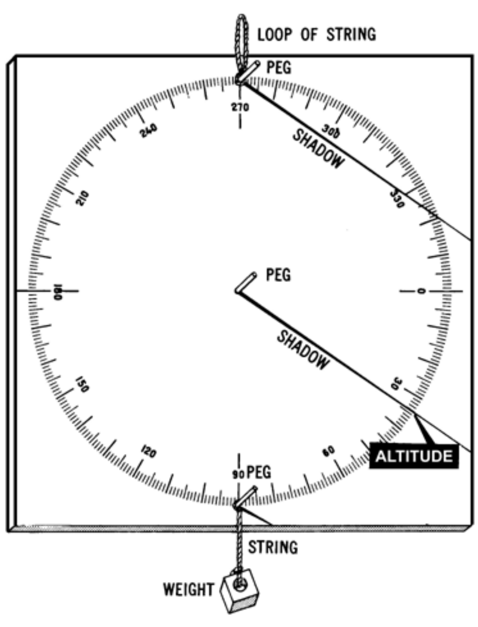


Figure 2608a. Improvised astrolabe; shadow method.

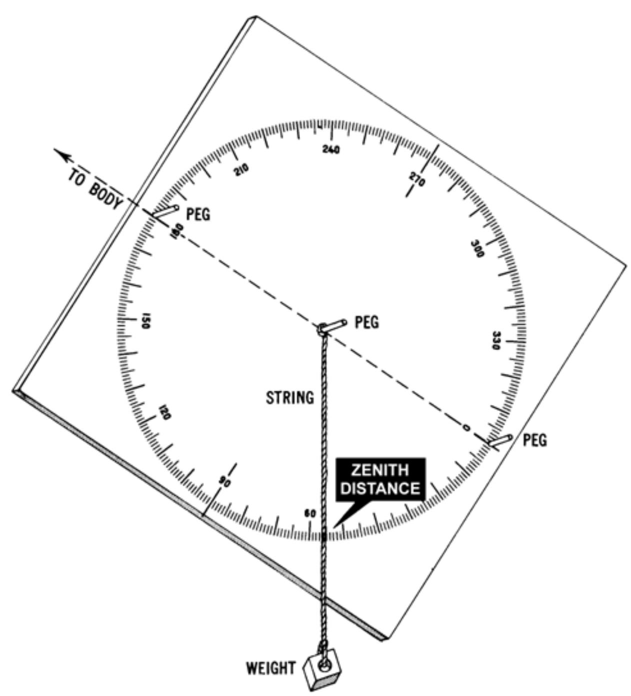


Figure 2608b. Improvised astrolabe; direct sighting method.

used for bodies other than the sun.

Whatever the technique, reverse the device for half the readings of a series, to minimize errors of construction. Generally, the circle method produces more accurate results than the right triangle method, described below.

2. Right triangle. A cross-staff can be used to establish one or more right triangles, which can be solved by measurement of the angle representing the altitude, either directly or by reconstructing the triangle. Another way of determining the altitude is to measure two of the sides of the triangle and divide one by the other to determine one of the trigonometric functions. This procedure, of course, requires a source of information on the values of trigonometric functions corresponding to various angles. If the cosine is found, Table 2604 can be used. The tabulated factors can be considered correct to one additional decimal for the value midway between the limited values (except that 1.00 is the correct value for 0° and 0.00 is the correct value for 90°) without serious error by emergency standards. Interpolation can then be made between such values.

By either protractor or table, most devices can be graduated in advance so that angles can be read directly. There are many variations of the right triangle method. Some of these are described below.

Two straight pieces of wood can be attached to each other in such a way that the shorter one can be moved along the longer, the two always being perpendicular to each other. The shorter piece is attached at its center. One end of the longer arm is held to the eye. The shorter arm is moved until its top edge is in line with the celestial body, and its bottom edge is in line with the horizon. Thus, two right triangles are formed, each representing half the altitude. For low altitudes, only one of the triangles is used, the long arm being held in line with the horizon. The length of half the short arm, divided by the length of that part of the long arm between the eye and the intersection with the short arm, is the tangent of half the altitude (the whole altitude if only one right triangle is used). The cosine can be found by dividing that part of the long arm between the eye and the intersection with the short arm by the slant distance from the eye to one end of the short arm. Graduations consist of a series of marks along the long arm indicating settings for various angles. The device should be inverted for alternate readings of a series.

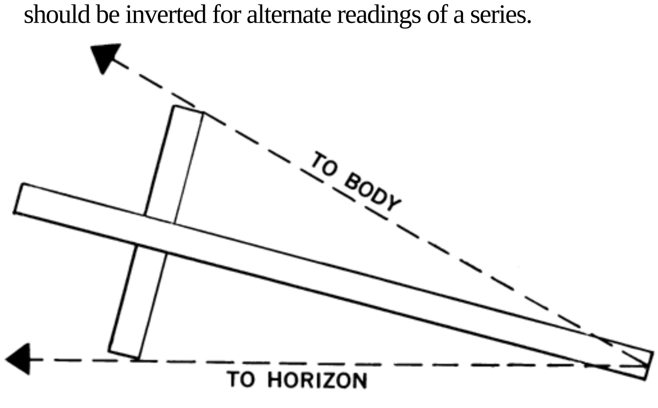


Figure 2608c. Improvised cross-staff.

A rule or any stick can be held at arm's length. The top of the rule is placed in line with the celestial body being observed, and the top of the thumb is placed in line with the horizon. The rule is held vertically. The length of rule above the thumb, divided by the distance from the eye to the top of the thumb, is the tangent of the angle observed. The cosine can be found by dividing the distance from the eye to the top of the thumb by the distance from the eye to the top of the rule. If the rule is tilted toward the eye until the minimum of rule is used, the distance from the eye to the middle of the rule is substituted for the distance from the eye to the top of the thumb, half the length of the rule above the thumb is used, and the angle found is multiplied by 2. Graduations consist of marks on the rule or stick indicating various altitudes. For the average observer each inch of rule will subtend an angle of about 2.3°, assuming an eye-to-ruler distance of 25 inches. This relationship is good to a maximum altitude of about 20°.

The accuracy of this relationship can be checked by comparing the measurement against known angles in the sky. Angular distances between stars can be computed by sight reduction methods, including *Pub. No. 229*, by using the declination of one star as the latitude of the assumed position, and the difference between the hour angles (or SHA's) of the two bodies as the local hour angle. The angular distance is the complement of the computed altitude. The angular distances between some well-known star pairs are: end stars of Orion's belt, 2.7°; pointers of the Big Dipper, 5.4°, Rigel to Orion's belt, 9.0°; eastern side of the great square of Pegasus, 14.0°; Dubhe (the pointer nearer Polaris) and Mizar (the second star in the Big Dipper, counting from the end of the handle), 19.3°.

The angle between the lines of sight from each eye is, at arm's length, about 6°. By holding a pencil or finger horizontally, and placing the head on its side, one can estimate an angle of about 6° by closing first one eye and then the other, and noting how much the pencil or finger appears to move in the sky.

The length of the shadow of a peg or nail mounted perpendicular to a horizontal board can be used as one side of an altitude triangle. The other sides are the height of the peg and the slant distance from the top of the peg to the end of the shadow. The height of the peg, divided by the length of the shadow, is the tangent of the altitude of the center of the sun. The length of the shadow, divided by the slant distance, is the cosine. Graduations consist of a series of concentric circles indicating various altitudes, the peg being at the common center. The device is kept horizontal by floating it in a bucket of water. Half the readings of a series are taken with the board turned 180° in azimuth.

Two pegs or nails can be mounted perpendicular to a board, with a weight hung from the one farther from the eye. The board is held vertically and the two pegs aligned with the body being observed. A finger is then placed over the string holding the weight, to keep it in position as the board is turned on its side. A perpendicular line is dropped from the peg nearer the eye, to the string. The body's altitude is the acute angle nearer the eye. For alternate readings of a series, the board should be inverted. Graduations consist of a series of marks

indicating the position of the string at various altitudes.

As the altitude decreases, the triangle becomes smaller. At the celestial horizon it becomes a straight line. No instrument is needed to measure the altitude when either the upper or lower limb is tangent to the horizon, as the sextant altitude is then 0°.

2609. Sextant Altitude Corrections

If altitudes are measured by a marine sextant, the usual sextant altitude corrections apply. If the center of the sun or moon is observed, either by sighting at the center or by shadow, the lower-limb corrections should be applied, as usual, and an additional correction of minus 16' applied. If the upper limb is observed, use minus 32'. If a weight is used as a plumb bob, or if the length of a shadow is measured, omit the dip (height of eye) correction.

If an almanac is not available for corrections, each source of error can be corrected separately, as follows:

If a sextant is used, the **index correction** should be determined and applied to all observations, or the sextant adjusted to eliminate index error.

Refraction is given to the nearest minute of arc in Table 2609. The value for a horizon observation is 34'. If the nearest 0.1° is sufficiently accurate, as with an improvised method of observing altitude, a correction of 0.1° should be applied for altitudes between 5° and 18°, and no correction applied for greater altitudes. Refraction applies to all observations, and is always minus.

Dip, in minutes of arc, is approximately equal to the square root of the height of eye, in feet. The dip correction applies to all observations in which the horizon is used as the horizontal reference. It is always a minus. If 0.1° accuracy is acceptable, no dip correction is needed for small boat heights of eye.

The **semidiameter** of the sun and moon is approximately 16' of arc. The correction does not apply to other bodies or to observations of the center of the sun and moon, by whatever method, including shadow. The correction is positive if the lower limb is observed, and negative if the upper limb is observed.

For emergency accuracy, **parallax** is applied to observations of the moon only. An approximate value, in minutes of arc, can be found by multiplying 57' by the factor from Table 2604, entering that table with altitude. For more accurate results, the factors can be considered correct to one additional decimal for the altitude midway between the limiting values (except that 1.00 is correct for 0° and 0.00 is correct for 90°), and the values for other altitudes can be found by interpolation. This correction is always positive.

For observations of celestial bodies on the horizon, the total correction for zero height of eye is:

Sun: Lower limb: (–)18', upper limb: (–)50'.
Moon: Lower limb: (+)39', upper limb: (+)7'.
Planet/Star: (-)34˚.

Dip should be added algebraically to these values.

Since the "sextant" altitude is zero, the "observed" altitude is equal to the total correction.

2610. Sight Reduction

Sight reduction tables should be used, if available. If not, use the compact sight reduction tables found in the *Nautical Almanac*. If trigonometric tables and the necessary formulas are available, they will serve the purpose. Speed in solution is seldom a factor in a lifeboat, but might be important aboard ship, particularly in hostile areas. If tables but no formulas are available, determine the mathematical knowledge possessed by the crew. Someone may be able to provide the missing information. If the formulas are available, but no tables, approximate natural values of the various trigonometric functions can be obtained graphically. Graphical solution of the navigational triangle can be made by the orthographic method explained in the chapter on Navigational Astronomy. A maneuvering board might prove helpful in the graphical solution for either trigonometric functions or altitude and azimuth. Very careful work will be needed for useful results by either method. Unless full navigational equipment is available, better results might be obtained by making separate determinations of latitude and longitude.

2611. Latitude Determination

Several methods are available for determining latitude; none requires accurate time.

Latitude can be determined using a **meridian altitude** of any body, if its declination is known. If accurate time, knowledge of the longitude, and an almanac are available, the observation can be made at the correct moment, as determined in advance. However, if any of these is lacking, or if an accurate altitude-measuring instrument is unavailable, a better procedure is to make a number of altitude observations before and after meridian transit. Then plot altitude versus time on graph paper, and the highest (or lowest, for lower transit) altitude is scaled from a curve faired through the plotted points. At small boat speeds, this procedure is not likely to introduce a significant error. The time used for plotting the observations need not be accurate, as elapsed time between observations is all that is needed, and this is not of critical accuracy. Any altitudes that are not consistent with others of the series should be discarded.

Latitude by Polaris is explained in Chapter 20, Sight Reduction. In an emergency, only the first correction is of practical significance. If suitable tables are not available, this correction can be estimated. The trailing star of Cassi-

Altitude	5°		6°		7°		8°		10°		12°		15°		21°		33°		63°		90°
Refraction		9'		8'		7'		6'		5'		4'		3'		2'		1'		0	

Table 2609. Refraction.

opeia (ε Cassiopeiae) and Polaris have almost exactly the same SHA. The trailing star of the Big Dipper (Alkaid) is nearly opposite Polaris and ε Cassiopeiae. These three stars, ε Cassiopeiae, Polaris, and Alkaid, form a line through the pole (approximately). When this line is horizontal, there is no correction. When it is vertical, the maximum correction of 56' applies. It should be added to the observed altitude if Alkaid is at the top, and subtracted if ∈ Cassiopeiae is at the top. For any other position, estimate the angle this line makes with the vertical, and multiply the maximum correction (56') by the factor from Table 2604, adding if Alkaid is higher than ∈ Cassiopeiae, and subtracting if it is lower. For more accurate results, the factor from Table 2604 can be considered accurate to one additional decimal for the mid-value between those tabulated (except that 1.00 is correct for 0° and 0.00 for 90°). Other values can be found by interpolation.

The **length of the day** varies with latitude. Hence, latitude can be determined if the elapsed time between sunrise and sunset can be accurately observed. Correct the observed length of day by adding 1 minute for each 15' of longitude traveled toward the east and subtracting 1 minute for each 15' of longitude traveled toward the west. The latitude determined by length of day is the value for the time of meridian transit. Since meridian transit occurs approximately midway between sunrise and sunset, half the interval may be observed and doubled. If a sunrise and sunset table is not available, the length of daylight can be determined graphically using a diagram on the plane of the celestial meridian, as explained in Chapter 15. A maneuvering board is useful for this purpose. This method cannot be used near the time of the equinoxes and is of little value near the equator. The moon can be used if moonrise and moonset tables are available. However, with the moon, the half-interval method is of insufficient accuracy, and allowance should be made for the longitude correction.

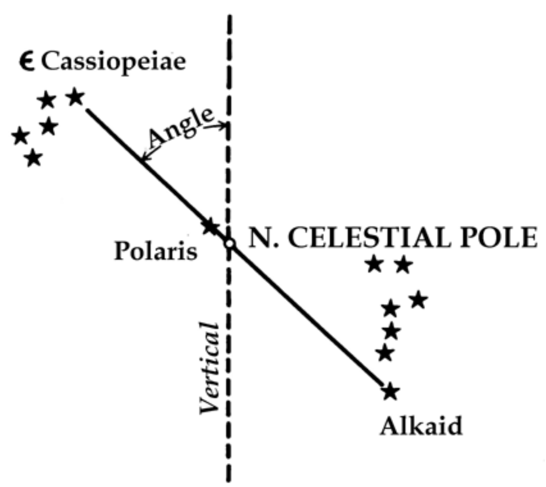


Figure 2611. Relative positions of ε Cassiopeiae, Polaris, and Alkaid with respect to the north celestial pole.

The declination of a **body in zenith** is equal to the latitude of the observer. If no means are available to measure altitude, the position of the zenith can be determined by holding a weighted string overhead.

2612. Longitude Determination

Unlike latitude, determining longitude requires accurate Greenwich time. All such methods consist of noting the Greenwich time at which a phenomenon occurs locally. In addition, a table indicating the time of occurrence of the same phenomenon at Greenwich, or equivalent information, is needed. Three methods may be used to determine longitude.

When a body is on the local celestial meridian, its GHA is the same as the longitude of the observer if in west longitude, or 360 - λ in east longitude. Thus, if the GMT of local **time of transit** is determined and a table of Greenwich hour angles (or time of transit of the Greenwich meridian) is available, longitude can be computed. If only the equation of time is available, the method can be used with the sun. This is the reverse of the problem of finding the time of transit of a body. The time of transit is not always apparent. If a curve is made of altitude versus time, as suggested previously, the time corresponding to the highest altitude is used in the determination of longitude. Under some conditions, it may be preferable to observe an altitude before meridian transit, and then again after meridian transit, when the body has returned to the same altitude as at the first observation. Meridian transit occurs midway between these two times. A body in the zenith is on the celestial meridian. If accurate azimuth measurement is available, note the time when the azimuth is 000° or 180°.

The difference between the observed GMT of **sunrise or sunset** and the LMT tabulated in the almanac is the longitude in time units, which can then be converted to angular measure. If the *Nautical Almanac* is used, this information is tabulated for each third day only. Greater accuracy can be obtained if interpolation is used for determining intermediate values. Moonrise or moonset can be used if the tabulated LMT is corrected for longitude. Planets and stars can be used if the time of rising or setting can be determined. This can be computed, or approximated using a diagram on the plane of the celestial meridian (See Chapter 15, Navigational Astronomy).

Either of these methods can be used in reverse to set a watch that has run down or to check the accuracy of a watch if the longitude is known. In the case of a meridian transit, the time need not be determined at the instant of transit. The watch is started, and the altitude is then measured several times before and after transit, or at equal altitudes before and after. The times of these observations are noted, and from them the time of meridian transit is determined. The difference between this time and the correct time of transit can then be used as a correction to reset the watch.

CHAPTER 27

NAVIGATION REGULATIONS

SHIP ROUTING

2700. Purpose And Types Of Routing Systems

Navigation, once truly independent throughout the world, is an increasingly regulated activity. The consequences of collision or grounding for a large, modern ship carrying tremendous quantities of high-value, perhaps dangerous cargo, are so severe that authorities have instituted many types of regulations and control systems to minimize the chances of loss. These range from informal and voluntary systems to closely controlled systems requiring compliance with numerous regulations. The regulations may concern navigation, communications, equipment, procedures, personnel, and many other aspects of ship management. This chapter will be concerned primarily with navigation regulations and procedures.

There are several specific types of regulation systems. For commonly used open ocean routes where risk of collision is present, the use of **recommended routes** separates ships going in opposite directions. In areas where ships converge at headlands, straits, and major harbors, **traffic separation schemes (TSS)** have been instituted to separate vessels and control crossing and meeting situations. Environmentally sensitive areas may be protected by **areas to be avoided** which prevent vessels of a certain size or carrying certain cargoes from navigating within specified boundaries. In confined waterways such as canals, lock systems, and rivers leading to major ports, local navigation regulations control ship movement.

2701. Definitions

The following terms relate to ship's routing:

Routing System: Any system of routes or routing measures designed to minimize the possibility of collisions between ships, including TSS's, two-way routes, recommended tracks, areas to be avoided, inshore traffic zones, precautionary areas, and deep-water routes.

Traffic Separation Scheme: A routing measure which separates opposing traffic flow with traffic lanes.

Separation Zone or Line: A zone or line which separates opposing traffic, separates traffic from adjacent areas, or separates different classes of ships from one another.

Traffic Lane: An area within which one-way traffic is established.

Roundabout: A circular traffic lane used at junctions of several routes, within which traffic moves counterclockwise around a separation point or zone.

Inshore Traffic Zone: The area between a traffic separation scheme and the adjacent coast, usually designated for coastal traffic.

Two-way Route: A two-way track for guidance of ships through hazardous areas.

Recommended Route: A route established for convenience of ship navigation, often marked with centerline buoys.

Recommended Track: A route, generally found to be free of dangers, which ships are advised to follow to avoid possible hazards nearby.

Deep-Water Route: A route surveyed and chosen for the passage of deep-draft vessels through shoal areas.

Precautionary Area: A defined area within which ships must use particular caution and should follow the recommended direction of traffic flow.

Area To Be Avoided: An area within which navigation by certain classes of ships is prevented because of particular navigational dangers or environmentally sensitive natural features.

Established Direction of Traffic Flow: The direction in which traffic within a lane must travel.

Recommended Direction of Traffic Flow: The direction in which traffic is recommended to travel.

There are various methods by which ships may be separated using Traffic Separation Schemes. The simplest

scheme might consist of just one method; more complex schemes will use several different methods together in a coordinated pattern to route ships to and from several areas at once. Schemes may be just a few miles in extent, or cover relatively large sea areas.

2702. Recommended Routes And Tracks

Recommended routes across the North Atlantic have been followed since 1898, when the risk of collision between increasing numbers of ships became too great, particularly at junction points. The International Convention for the Safety of Life at Sea (SOLAS) codifies the use of certain routes. These routes vary with the seasons, with winter and summer tracks chosen so as to avoid iceberg-prone areas. These routes are often shown on charts, particularly small scale ones, and are generally used to calculate distances between ports in tables.

Recommended routes consists of single tracks, either one-way or two-way. Two-way routes show the best water through confined areas such as inland routes among islands and reefs. Ships following these routes can expect to meet other vessels head-on and engage in normal passings. One-way routes are generally found in areas where many ships are on similar or opposing courses. They and are intended to separate opposing traffic so that most maneuvers are overtaking situations instead of the more dangerous meeting situation.

2703. Charting Recommended Routes

Recommended routes and recommended tracks are generally indicated on charts by black lines, with arrowheads indicating the desired direction of traffic. Not all recommended routes are charted. DMA charts generally depict recommended routes only on modified facsimiles made directly from foreign charts. In all cases, recommended routes are discussed in detail in the *Sailing Directions*.

TRAFFIC SEPARATION SCHEMES

2704. Traffic Separation Schemes (TSS)

In 1961, representatives from England, France, and Germany met to discuss ways to separate traffic in the congested Straits of Dover and subsequently in other congested areas. Their proposals were submitted to the International Maritime Organization (IMO) and were adopted in general form. IMO expanded on the proposals and has since instituted a system of **Traffic Separation Schemes (TSS)** throughout the world.

The IMO is the only international body responsible for establishing and recommending measures for ship's routing in international waters. It does not attempt to regulate traffic within the territorial waters of any nation.

In deciding whether or not to adopt a TSS, IMO considers the aids to navigation system in the area, the state of hydrographic surveys in the area, the scheme's adherence to accepted standards of routing, and the International Rules of the Road. The selection and development of TSS's are the responsibility of individual governments, who may seek IMO adoption of their plans, especially if the system extends into international waters.

Governments may develop and implement TSS's not adopted by the IMO, but in general only IMO-adopted schemes are charted. Rule 10 of the International Regulations for Preventing Collisions at Sea (Rules of the Road) addresses the subject of TSS's. This rule specifies the actions to be taken by various classes of vessels in and near traffic schemes.

Traffic separation schemes adopted by the IMO are listed in *Ship's Routing*, a publication of the IMO, 4 Albert Embankment, London SE1 7SR, United Kingdom. Because of differences in datums, chartlets in this publication which depict the various schemes must not be used either for navigation or to chart the schemes on navigational charts. The *Notice to Mariners* should be consulted for charting details.

2705. Methods Of Traffic Separation

A number of different methods of separating traffic have been developed, using various zones, lines, and defined areas. One or more methods may be employed in a given traffic scheme to direct and control converging or passing traffic. These are discussed below. Refer to definitions in section 2701.

Method 1. Separation of opposing streams of traffic by separation zones or lines. In this method, typically a central separation zone is established within which ships are not to navigate. The central zone is bordered by traffic lanes with established directions of traffic flow. The lanes are bounded on the outside by limiting lines.

Method 2. Separation of opposing streams of traffic by natural features or defined objects. In this method islands, rocks, or other features may be used to separate traffic. The feature itself becomes the separation zone.

Method 3. The separation of through traffic from local traffic by provision of inshore traffic zones. Outside of traffic schemes, ships may generally navigate in any direction. Inshore traffic zones provide an area within which local traffic may travel at will without interference with through

traffic in the lanes. Inshore zones are separated from traffic lanes by separation zones or lines.

Method 4. Division of traffic from several different direction into sectors. This approach is used at points of convergence such as pilot stations and major entrances.

Method 5. Routing traffic through junctions of two or more major shipping routes. The exact design of the scheme in this method varies with conditions. It may be a circular or rectangular precautionary area, a roundabout, or a junction of two routes with crossing routes and directions of flow well-defined.

2706. Representing TSS's On Charts

See Figure 2706. Depiction of TSS's on charts uses magenta (purple) as the primary color. Zones are shown by purple tint, limits are shown by T-dashes such as are used in other maritime limits, and lines are dashed. Arrows are open-lined or dashed-lined depending on use. Special provisions applying to a scheme may be mentioned in notes on the chart. Deep water routes will be marked with the designation "DW" in bold purple letters, and the least depth may be indicated.

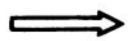
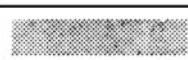
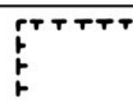
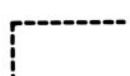
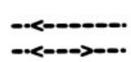
Routing term	Symbol	Description	Applications
1 Established direction of traffic flow		Outlined arrow	Traffic separation schemes and deep-water routes (when part of a traffic lane)
2 Recommended direction of traffic flow		Dashed outlined arrow	Precautionary areas, two-way routes, recommended routes and deep-water routes
3 Separation lines		Tint, 3 mm wide	Traffic separation schemes and between traffic separation schemes and inshore traffic zone
4 Separation zones		Tint, may be any shape	Traffic separation schemes and between traffic separation schemes and inshore traffic zones
5 Limits of restricted areas (charting term)		T-Shaped dashes	Areas to be avoided and defined ends of inshore traffic zones
6 General maritime limits (charting term)		Dashed line	Traffic separation schemes, precautionary areas, two-way routes and deep-water routes
7 Recommended tracks: one-way two-way		Dashed lines with arrowheads (colour black)	Generally reserved for use by charting authorities
8 Recommended routes		Dashed line and dashed outlined arrows	Recommended routes
9 Precautionary areas		Precautionary symbol	Precautionary areas

Figure 2706. Traffic separation scheme symbology. On charts the symbols are usually in magenta.

2707. Use Of Traffic Separation Schemes

A TSS is not officially approved for use until adopted by the IMO. Once adopted, it is implemented as of a certain time and date, as announced in the *Notice to Mariners* and perhaps through other means. The *Notice to Mariners* will also describe the scheme's general location and purpose and give specific directions in the chart correction section on plotting the various zones and lines which define it. These corrections usually apply to several charts. Because the charts may range in scale from quite small to very large, the corrections for each should be followed closely. The positions for the various features may be slightly different from chart to chart due to differences in rounding off positions or chart datum.

A TSS may be amended for periods of time ranging from a few hours to several years. Underwater construction works, surveying, dredging, and other transitory activities will be noted by radio broadcast, *Local Notice To Mariners*, or other means. Longer duration activities such as placement of oil drilling rigs, platforms, or pipelines may require a charted change to the scheme, which may become a permanent feature. These will be *Notice to Mariners* items.

Use of TSS's by all ships is recommended. They are intended for use in all weather, day and night. Adequate aids to navigation are a part of all TSS's. There is no special right of one ship over another in TSS's because the Rules of the Road apply in all cases. Deep-water routes should be avoided by ships which do not need them to keep them clear for deep-draft vessels. Ships need not keep strictly to the courses indicated by the arrows, but are free to navigate as necessary within their lanes to avoid other traffic. The signal "YG" is provided in the International Code of Signals to indicate to another ship: "You appear not to be complying with the traffic separation scheme."

TSS's are discussed in detail in the *Sailing Directions* for the areas where they are found.

2708. Areas To Be Avoided

Areas to be avoided are adopted by the IMO and are usually established to prevent possible grounding of tankers and other ships carrying hazardous cargo in environmentally sensitive areas. They may also be established to keep particular classes of ships away from areas where navigation is particularly hazardous.

They are depicted on charts by dashed lines or T-dashed lines, either point to point straight lines or as a circle centered on a feature in question such as a rock or island. The smallest may cover less than a mile in extent; the largest may cover hundreds of square miles of coral reefs or dangerous shoals. Notes on the appropriate charts and in Sailing Directions tell which classes of ships are excluded from the area.

2709. Special Rules

Certain special rules adopted by IMO apply in constricted areas such as the Straits of Malacca and Singapore, the English Channel and Dover Strait, and in the Gulf of Suez. These regulations are summarized in the appropriate *Sailing Directions (Planning Guides)*. For a complete summary of worldwide ships' routing measures, the IMO publication *Ship's Routing* should be obtained. See paragraph 2704.

VESSEL TRAFFIC SERVICES (VTS)

2710. Development And Purpose

The purpose of Vessel Traffic Services (VTS) is to provide active monitoring and navigational advice for vessels in particularly confined and busy waterways. There are two main types of VTS, surveilled and non-surveilled. Surveilled systems consist of one or more land-based radar sites which output their signals to a central location where operators monitor and to a certain extent control traffic flows. Non-surveilled systems consist of one or more calling-in points at which ships are required to report their identity, course, speed, and other data to the monitoring authority.

Vessel Traffic Services in the U.S. are implemented under the authority of the Ports and Waterways Safety Act of 1972 (Public Law 92-340 as amended) and the St. Lawrence Seaway Act (Public Law 358). They encompass a wide range of techniques and capabilities aimed at preventing vessel collisions, rammings, and groundings in the harbor/harbor approach and inland waterway phase of navigation. They are also designed to expedite ship movements, increase transportation system capacity, and improve all-weather operating capability.

A VHF-FM communications network forms the basis of most major services. Transiting vessels make position reports to an operations center by radiotelephone and are in turn provided with accurate, complete, and timely navigational safety information. The addition of a network of radars for surveillance and computer-assisted tracking and tagging, similar to that used in air traffic control, allows the VTS to play a more significant role in marine traffic management, thereby decreasing vessel congestion, critical encounter situations, and the probability of a marine casualty resulting in environmental damage. Surveilled VTS's are found in many large ports and harbors where congestion is a safety and operational hazard. Less sophisticated services have been established in other areas in response to hazardous navigational conditions according to the needs and resources of the authorities.

2711. Brief History Of VTS

Since the early 1960's the U.S. Coast Guard has been

investigating various concepts by which navigational safety can be improved in the harbor and harbor approach areas. Equipment installations in various ports for this investigation have included shore-based radar; low light level, closed-circuit television (LLL-CCTV); VHF-FM communications; broadcast television; and computer driven electronic situation displays.

In 1962 an experimental installation called **Ratan** (Radar and Television Aid to Navigation) was completed in New York Harbor. In this system a radar at Sandy Hook, New Jersey, scanned the approaches to the harbor. The radar video, formatted by a scan conversion storage tube, was broadcast by a television band UHF transmitter. This enabled mariners to observe on commercial television sets the presentation on the radarscope at Sandy Hook. The mariner could identify his vessel on the television screen by executing a turn and by observing the motions of the targets. The high persistency created by the scan converter provided target "tails" which aided in observing target movement. This Ratan experiment was discontinued primarily because of allocation of the commercial television frequency spectrum for other purposes.

In January 1970 the Coast Guard established a harbor radar facility in San Francisco to gather data on vessel traffic patterns. The information was used to determine parameters for new equipment procurements. The initial installation consisted of standard marine X-band (3-centimeter) search radars located on Point Bonita and Yerba Buena Island in San Francisco Bay. Radar video was relayed from these two radar sites to a manned center colocated with the San Francisco Marine Exchange. When the parameter definition work was completed, VHF-FM communications equipment was added to enable communications throughout the harbor area. This experimental system, previously called Harbor Advisory Radar (HAR) was designated in August 1972 as an operational Vessel Traffic System (VTS); a continuous radar watch with advisory radio broadcasts to traffic in the harbor was provided. This change from HAR to VTS coincided with the effective date of the Ports and Waterways Safety Act of 1972, authorizing the U.S. Coast Guard to install and operate such systems in United States waters to increase vessel safety and there by protect the environment.

In late 1972 improved developmental radar systems were installed side by side with the operational system, operated by a new research evaluation center at Yerba Buena Island. Redundant operator-switchable transceivers provided 50 kW peak power and incorporated receivers with large dynamic ranges of automatic gain control giving considerable protection against receiver saturation by interfering signals and interference by rain and sea clutter. Parabolic antennas with apertures of 27 feet (8.2 meters) and beam widths of 0.3 degrees improved the radar system accuracy. Variable pulse lengths (50 and 200 nanoseconds), three pulse repetition rates (1000, 2500, and 4000 pps), two receiver bandwidths (22 MHz and 2 MHz), and three antenna polarizations (horizontal, vertical, and circular) were provided to evaluate the optimum parameters for future procurements.

After a period of extensive engineering evaluation, the radar system was accepted in May 1973 as an operational replacement for the equipment installed earlier at the HAR.

In 1980 an analysis indicated that a modified version of the Coast Guard standard shipboard radar would meet all the VTS standard operating requirements. Additionally, it was more cost effective to procure and maintain than the specially designed, non-standard radar. After a period of evaluation at VTS San Francisco and with certain technical modifications, the standard radar was accepted for VTS use. The radar includes a tracking system which enhances the radar capability by allowing the VTS to track up to 20 targets automatically. The PPI can operate in an environment that is half as bright as a normal room with an option for a TV type display that can operate under any lighting conditions. These new radars are also required to provide data to a computer system, have 60 navigational line capability, and display ranges in yards or nautical miles.

The new radar was installed in VTS Prince William Sound in August 1984. VTS Houston-Galveston's radar was replaced in January 1985. VTS San Francisco radars were replaced in May 1985. VTS New York reopened in late 1990 and will continue to add coverage areas until the project is completed in 1995.

2712. Operational Systems

VTS New York became operational in December 1990. It had been open previously but was closed in 1988 due to a change in funding priorities.

This VTS has the responsibility of coordinating vessel traffic movements in the busy ports of New York and New Jersey. The VTS New York area includes the entrance to the harbor via Ambrose and Sandy Hook Channels, through the Verrazano Narrows Bridge to the Brooklyn Bridge in the East River, to the Holland Tunnel in the Hudson River, and the Kill Van Kull including Newark Bay. Future plans call for the VTS area to be expanded to include the East River to Throgs Neck, all of Arthur Kill, and Raritan Bay.

VTS New York is presently undergoing an upgrade which includes the installation of state-of-the-art equipment in a new operations center. The current operation uses surveillance data provided by 4 radar sites and 3 closed circuit TV sites. VTS communications are on VHF/FM channels 12 and 14.

VTS San Francisco was commissioned in August of 1972. When the original radar system became operational in May 1973, the control center for VTS San Francisco was shifted to the Yerba Buena Island. This center was designated a Vessel Traffic Center (VTC).

As of early 1985, the major components of the system include a Vessel Traffic Center at Yerba Buena Island, two high resolution radars, a VHF-FM communications network, a traffic separation scheme, and a vessel movement

reporting system (VMRS). Channels 12 and 14 are the working frequencies. In 1985, all existing radar equipment was replaced with the standard Coast Guard radar.

VTS San Francisco also operates an Offshore Vessel Movement Reporting System (OVMRS). The OVMRS is completely voluntary and operates using a broadcast system with information provided by participants.

VTS Puget Sound became operational in September 1972 as the second Vessel Traffic Service. It collected vessel movement report data and provided traffic advisories by means of a VHF-FM communications network. In this early service a VMRS was operated in conjunction with a Traffic Separation Scheme (TSS), without radar surveillance. Operational experience gained from this service and VTS San Francisco soon proved the expected need for radar surveillance in those services with complex traffic flow.

In 1973 radar coverage in critical areas of Puget Sound was provided. Efforts to develop a production generation of radar equipment for future port development were initiated. To satisfy the need for immediate radar coverage, redundant military grade Coast Guard shipboard radar transceivers were installed at four Coast Guard light stations along the Admiralty Inlet part of Puget Sound. Combination microwave radio link and radar antenna towers were installed at each site. Radar video and azimuth data, in a format similar to that used with VTS San Francisco, were relayed by broad band video links to the VTC in Seattle. At that Center, standard Navy shipboard repeaters were used for operator display. Although the resolution parameters and display accuracy of the equipment were less than those of the VTS San Francisco equipment, the use of a shorter range scale (8 nautical miles) and overlapping coverage resulted in very satisfactory operation. In December 1980 additional radar surveillance was added in the Strait of Juan De Fuca and Rosario Strait, as well as increased surveillance of the Seattle area, making a total of 10 remote radar sites.

The communications equipment was upgraded in July 1991 to be capable of a two frequency, four sector system. Channels 5A and 14 are the frequencies for VTS Puget Sound. A total of 13 Communication sites are in operation (3 extended area sites, 10 low level sites). The 3 extended area sites allow the VTS the ability to communicate in a large area when needed. The low level sites can be used in conjunction with one another without interference, and have greatly reduced congestion on the frequency. VTS Puget Sound now covers the Strait of Juan de Fuca, Rosario Strait, Admiralty Inlet, and Puget Sound south as far as Olympia.

The major components of the system include the Vessel Traffic Center at Pier 36 in Seattle; a VHF-FM communications network; a traffic separation scheme; radar surveillance of about 80% of the VTS area, and a Vessel Movement Reporting System. Regulations are in effect which require certain classes of vessels to participate in the system and make movement reports at specified points. The traffic separation scheme in the Strait of Juan de Fuca was extended as far west as Cape Flattery in March 1975 in cooperation with Canada and was formally adopted by the International Maritime Organization in 1982.

Under an agreement between the United States and Canada, regulations for the Strait of Juan de Fuca took effect in 1984. The Cooperative Vessel Traffic Management System (CVTMS) divides responsibility among the two Canadian VTS's and VTS Puget Sound.

VTS Houston-Galveston became operational in February 1975 as the third Vessel Traffic Service. The operating area is the Houston Ship Channel from the sea buoy to the Turning Basin (a distance of 53 miles) and the side channels to Galveston, Texas City, Bayport, and the Intracoastal Waterway. The area contains approximately 70 miles of restricted waterways. The greater part of the Houston Ship Channel is 400 feet wide with depths of 36-40 feet. Several bends in the channel are in excess of 90 degrees.

The major components of the system include the VTC at Galena Park, Houston; a VHF-FM communications network; low light level, closed circuit television (LLL-CCTV) surveillance covering approximately 3 miles south of Morgan's Point west through the ship channel to City Dock #27 in Houston; a Vessel Movement Reporting System; and a radar surveillance system covering lower Galveston Bay approaches, Bolivar Roads, and Lower Galveston Bay.

A second radar was installed in 1994. This radar will provide surveillance coverage between the Texas City channel and Morgan's Point.

VTS Prince William Sound is required by The Trans-Alaska Pipeline Authorization Act (Public Law 93-153), pursuant to authority contained in Title 1 of the Ports and Waterways Safety Act of 1972 (86 Stat. 424, Public Law 92-340).

The southern terminus of the pipeline is on the south shoreline of Port Valdez, at the Alyeska Pipeline Service Company tanker terminal. Port Valdez is at the north end of Prince William Sound, and Cape Hinchinbrook is at the south entrance.

Geographically, the area is comprised of deep open waterways surrounded by mountainous terrain. The only constrictions to navigation are at Cape Hinchinbrook, the primary entrance to Prince William Sound, and at Valdez Narrows, the entrance to Port Valdez.

The vessel traffic center is located in Valdez. The system is composed of two radars, two major microwave data relay systems, and a VMRS which covers Port Valdez, Prince William Sound, and Gulf of Alaska. There is also a vessel traffic separation scheme from Cape Hinchinbrook to Valdez Arm.

The Coast Guard is installing a dependent surveillance system to improve its ability to track tankers transiting Prince William Sound. To extend radar coverage the length of the traffic lanes in Prince William Sound would require several radars at remote, difficult-to-access sites and an extensive data relay network. As an alternative to radar, the Coast Guard is installing a dependent surveillance system that will require vessels to carry posi-

tion and identification reporting equipment. The ability to supplement radar with dependent surveillance will bridge the gap in areas where conditions dictate some form of surveillance and where radar coverage is impractical. Once the dependent surveillance information is returned to the vessel traffic center, it will be integrated with radar data and presented to the watchstander on an electronic chart display.

REGULATED WATERWAYS

2713. Purpose And Authorities

In confined waterways not considered international waters, local authorities may establish certain regulations for the safe passage of ships and operate waterway systems consisting of locks, canals, channels, and ports. This occurs generally in very busy or very highly developed waterways which form the major constrictions on international shipping routes. The Panama Canal, St. Lawrence Seaway, and the Suez Canal represent systems of this type. Nearly all ports and harbors have a body of regulations concerning the operation of vessels within the port limits, particularly if locks and other structures are part of the system. The regulations covering navigation through these areas are typically part of a much larger body of regulations relating to assessment and payment of tariffs and tolls, vessel condition and equipment, personnel, communications equipment, and many other factors. In general the larger the investment in the system, the larger will be the body of regulations which control it.

Where the waterway separates two countries, a joint authority may be established to administer the regulations, collect tolls, and operate the system, as in the St. Lawrence Seaway.

Copies of the regulations are usually required to be aboard each vessel in transit. These regulations are available from the authority in charge or an authorized agent. Summaries of the regulations are contained in the appropriate volumes of the *Sailing Directions (Enroute)*.

CHAPTER 28

GLOBAL MARITIME DISTRESS AND SAFETY SYSTEM

DEVELOPMENT

2800. Introduction

The **Global Maritime Distress and Safety System (GMDSS)** represents a significant improvement in marine safety over the previous system of short range and high seas radio transmissions. Its many parts include satellite as well as advanced terrestrial communications systems. Operational service of the GMDSS began on 1 February 1992, with full implementation scheduled by 1 February 1999.

2801. Background

The GMDSS was adopted by amendments in 1988 by the Conference of Contracting Governments to the International Convention for the Safety of Life at Sea (SOLAS), 1974. This was the culmination of more than a decade of work by the International Maritime Organization (IMO) in conjunction with the International Telecommunications Union (ITU), International Hydrographic Organization (IHO), World Meteorological Organization (WMO), International Maritime Satellite Organization (INMARSAT), and others.

The GMDSS offers the greatest advancement in maritime safety since the enactment of regulations following the Titanic disaster in 1912. It is an automated ship-to-ship, shore-to-ship and ship-to-shore system covering distress alerting and relay, the provision of **maritime safety information (MSI)** and basic communication links. Satellite and advanced terrestrial systems are incorporated into a modern communications network to promote and improve safety of life and property at sea throughout the world. The equipment required on board ships will depend not on their tonnage, but rather on the sea area in which the vessel operates. This is fundamentally different from the previous system, which based requirements on vessel size alone. The greatest benefit of the GMDSS is that it vastly reduces the chances of ships sinking without a trace and enables search and rescue (SAR) operations to be launched without delay.

SHIP REQUIREMENTS

2802. Ship Carriage Requirements

By the terms of the SOLAS Convention, the GMDSS provisions apply to cargo ships of 300 gross tons and over and ships carrying more than 12 passengers on international voyages. Unlike previous shipboard carriage regulations that specified equipment according to *size* of vessel, the GMDSS carriage requirements stipulate equipment according to the *area* the vessel operates in. These sea areas are designated as follows:

Sea Area A1 An area within the radiotelephone coverage of at least one VHF coast station in which continuous Digital Selective Calling (DSC - a radio receiver that performs distress alerting and safety calling on HF, MF and VHF frequencies) is available, as may be defined by a Contracting Government to the 1974 SOLAS Convention. This area extends from the coast to about 20 miles offshore.

Sea Area A2 An area, excluding sea area A1, within the radiotelephone coverage of at least one MF coast station in which continuous DSC alerting is available, as may be defined by a Contracting Government. The general area is from the A1 limit out to about 100 miles offshore.

Sea Area A3 An area, excluding sea areas A1 and A2, within the coverage of an INMARSAT geostationary satellite in which continuous alerting is available. This area is from about 70°N to 70°S.

Sea Area A4 All areas outside of sea areas A1, A2 and A3. This area includes the polar regions, where geostationary satellite coverage is not available.

Ships at sea must be capable of the following functional GMDSS requirements:

1. Ship-to-shore distress alerting.
2. Shore-to-ship distress alerting.
3. Ship-to-ship distress alerting.
4. SAR coordination.
5. On-scene communications.
6. Transmission and receipt of emergency locating signals.
7. Transmission and receipt of MSI.
8. General radio communications.
9. Bridge-to-bridge communications.

To meet the requirements of the functional areas above the following is a list of the minimum communications equipment needed for all ships:

1. VHF radio capable of transmitting and receiving DSC on channel 70 and radio telephony on channels 6, 13 and 16.
2. Radio receiver capable of maintaining a continuous DSC watch on channel 70 VHF.
3. Search and rescue transponders (SART), a minimum of two, operating in the 9 GHz band.
4. Receiver capable of receiving NAVTEX broadcasts anywhere NAVTEX service is available.
5. Receiver capable of receiving SafetyNET anywhere NAVTEX is not available.
6. Satellite emergency position indicating radiobeacon (EPIRB), manually activated or float-free self-activated.
7. Two-way handheld VHF radios (two sets minimum on 300-500 gross tons cargo vessels and three sets minimum on cargo vessels of 500 gross tons and upward and on all passenger ships).
8. Until 1 Feb. 1999, a 2182 kHz watch receiver.

Additionally, each sea area has its own requirements under GMDSS which are as follows:

Sea Area A1

1. General VHF radio telephone capability.
2. Free-floating EPIRB transmitting DSC on channel 70 VHF, or satellite EPIRB.
3. Capability of initiating a distress alert from a navigational position using DSC on either VHF, HF or MF; manually activated EPIRB; or Ship Earth Station (SES).

Sea Areas A1 and A2

1. Radio telephone MF 2182 kHz and DSC on 2187.5 kHz.
2. Equipment capable of maintaining a continuous DSC watch on 2187.5 kHz.
3. General working radio communications in the MF band 1605-4000 kHz, or INMARSAT SES.
4. Capability of initiating a distress alert by HF (using DSC), manual activation of an EPIRB, or INMARSAT SES.

Sea Areas A1, A2 and A3

1. Radio telephone MF 2182 kHz and DSC 2187.5 kHz.
2. Equipment capable of maintaining a continuous DSC watch on 2187.5 kHz.
3. INMARSAT A, B or C (class 2) SES Enhanced Group Call (EGC), or HF as required for sea area A4.
4. Capability of initiating a distress alert by two of the following:
   a. INMARSAT A, B or C (class 2) SES.
   b. Manually activated satellite EPIRB.
   c. HF/DSC radio communication.

Sea Area A4

1. HF/MF receiving and transmitting equipment for band 1605-27500 kHz using DSC, radiotelephone and direct printing.
2. Equipment capable of selecting any safety and distress DSC frequency for band 4000-27500 kHz, maintaining DSC watch on 2187.5, 8414.5 kHz and at least one additional safety and distress DSC frequency in the band.
3. Ability to initiate a distress alert from a navigational position via the Polar Orbiting System on 406 MHz (manual activation of 406 MHz satellite EPIRB).

COMMUNICATIONS

2803. The INMARSAT System

The **International Maritime Satellite Organization (INMARSAT)**, a key player within GMDSS, is an international consortium comprising over 75 international partners who provide maritime safety communications for ships at sea. In accordance with its convention, INMARSAT provides the space segment necessary for improving distress communications, efficiency and management of ships, as well as maritime correspondence services.

The basic components of the INMARSAT system include the INMARSAT **space segment, Land Earth Stations (LES)**, also referred to as **Coast Earth Stations (CES)**, and mobile **Ship Earth Stations (SES)**.

The INMARSAT space segment consists of 11 geostationary satellites. Four operational INMARSAT satellites provide primary coverage, four additional satellites (including satellites leased from the European Space Agency (ESA) and the International Telecommunications Satellite Organization (INTELSAT)) serve as spares and three remaining satellites (leased from COMSAT Corporation, the U.S. signatory to INMARSAT) serve as back-ups.

The polar regions are not visible to the operational satellites and coverage is available from 70°N to 70°S. Satellite coverage (Figure 2803) is divided into four regions, which are:

1. Atlantic Ocean - East (AOR-E)
2. Atlantic Ocean - West (AOR-W)
3. Pacific Ocean (POR)
4. Indian Ocean (IOR)

The LES's provide the link between the Space Segment and the land-based National/International fixed communications networks. These communications networks are funded and operated by the authorized communications authorities of a participating nation. This network links registered information providers to the LES. The data then travels from the LES to the INMARSAT **Network Coordination Station (NCS)** and then down to the SES's on ships at sea. The SES's provide two-way communications between ship and shore. **INMARSAT A**, the original INMARSAT system, operates at a transfer rate of up to 9600 bits per second and is telephone, telex and facsimile (fax) capable. It is being replaced by a similarly sized **INMARSAT B** system that uses digital technology to give better quality fax and higher data transmission rates.

INMARSAT C provides a **store and forward** data messaging capability (but no voice) at 600 bits per second and was designed specifically to meet the GMDSS requirements for receiving MSI data on board ship. These units are small, lightweight and use an omni-directional antenna.

2804. SafetyNET

SafetyNET is a service of INMARSAT C's **Enhanced Group Call (EGC)** system. The EGC system (Figure 2804) is a method used to specifically address particular regions or ships. Its unique addressing capabilities allow messages to be sent to all vessels in both fixed geographical areas or to predetermined groups of ships. SafetyNET is the service designated by the IMO through which ships receive maritime safety information. The other service under the EGC system, called **FleetNET**, is used by commercial companies to directly (and privately) communicate to their individual fleets.

SafetyNET is an international direct-printing satellite-based service for the promulgation of navigational and meteorological warnings, and distress alerts, forecasts, and other safety messages. It fulfills an integral role in GMDSS as developed by the IMO. The ability to receive SafetyNET service information is necessary for all ships that sail beyond coverage of NAVTEX (approximately 200 miles from shore) and is recommended to all administrations having the

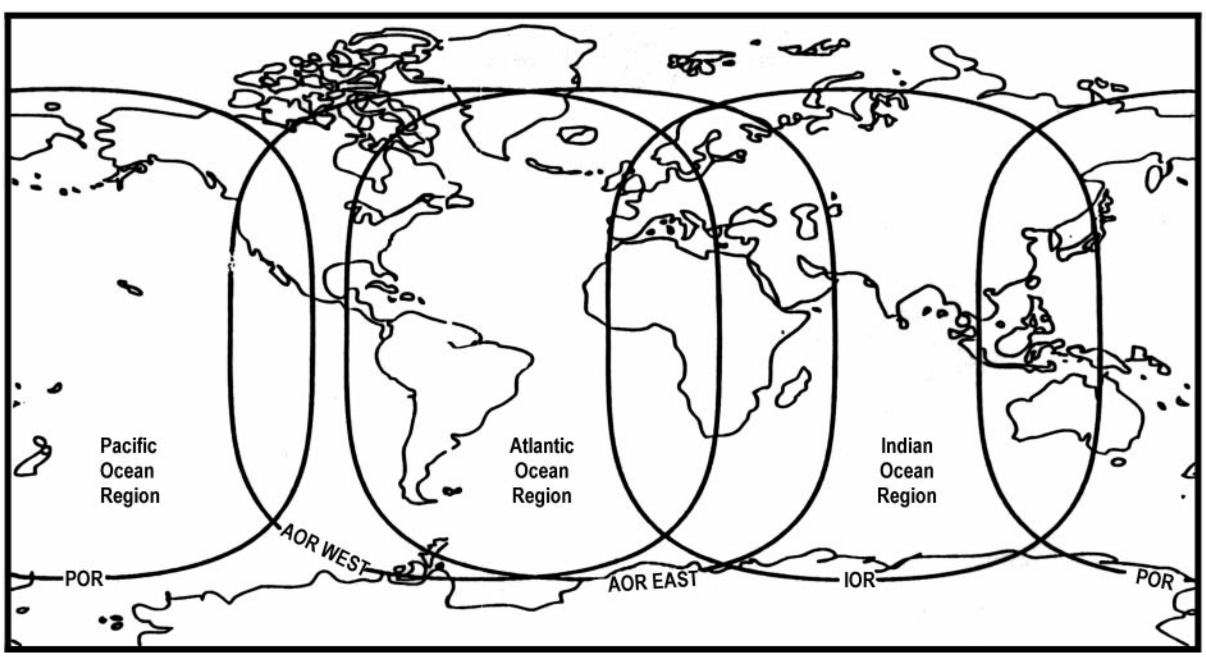


Figure 2803. The four regions of INMARSAT coverage.

responsibility for marine affairs and mariners who require effective MSI service in waters not served by NAVTEX.

SafetyNET can direct a message to a given geographic area based on EGC addressing. The area may be fixed, as in the case of a NAVAREA or weather forecast area, or it may be uniquely defined by the originator. This is particularly useful for messages such as local storm warnings or a ship-to-shore distress alert for which it would be inappropriate to alert ships in an entire ocean region.

SafetyNET messages can be originated by a **Registered Information Provider** anywhere in the world and broadcast to the appropriate ocean area through an INMARSAT-C LES. Messages are broadcast according to their priority (i.e., Distress, Urgent, Safety, and Routine).

Virtually all navigable waters of the world are covered by the operational satellites in the INMARSAT system. Each satellite broadcasts EGC traffic on a designated channel. Any ship sailing within the coverage area of an INMARSAT satellite will be able to receive all the SafetyNET messages broadcast over this channel. The EGC channel is optimized to enable the signal to be monitored by SES's dedicated to the reception of EGC messages. This capability can be built into other standard SES's. It is a feature of satellite communications that reception is not generally affected by the position of the ship within the ocean region, atmospheric conditions, or time of day.

Messages can be transmitted either to geographic areas (area calls) or to groups of ships (group calls):

1. **Area calls** can be to a fixed geographic area such as one of the 16 NAVAREA's or to a temporary geographic area selected by the originator. Area calls will be received automatically by any ship whose receiver has been set to one or more fixed areas or recognizes an area by geographic position.

2. **Group calls** will be received automatically by any ship whose receiver acknowledges the unique group identity associated with a particular message.

Reliable delivery of messages is ensured by forward error correction techniques. Experience has demonstrated that the transmission link is generally error-free and low error reception is achieved under normal circumstances.

Given the vast ocean coverage by satellite, some form of discrimination and selectivity in printing the various messages is required. Area calls will be received by all ships within the ocean region coverage of the satellite; however, they will be printed only by those receivers that recognize the fixed area or the geographic position in the message. The message format includes a **preamble** that enables the microprocessor in a ship's receiver to decide to print those MSI messages that relate to the present position, intended route or a fixed area programmed by the operator. This preamble also allows suppression of certain types of MSI that are not relevant to a particular ship. As each message will also have a

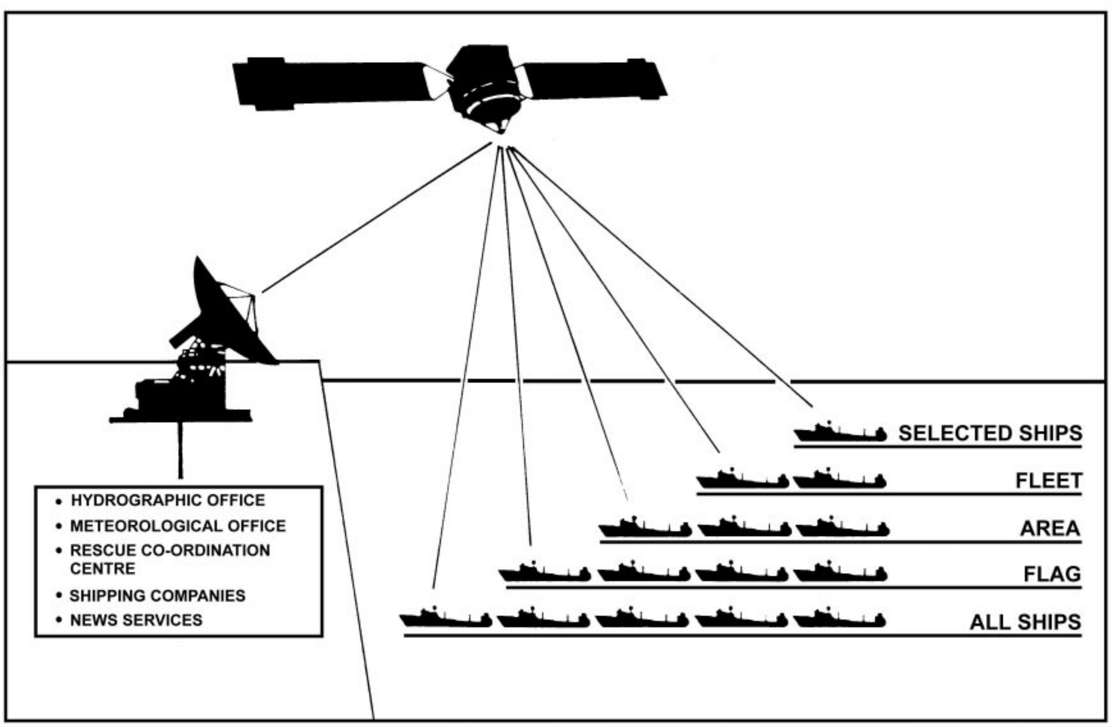


Figure 2804. SafetyNET EGC concept.

unique identity, the reprinting of messages already received correctly is automatically suppressed.

MSI is promulgated by various information providers around the world. Messages for transmission through the SafetyNET service will, in many cases, be the result of co-ordination between authorities. Information providers will be authorized to broadcast via SafetyNET by IMO. Authorized information providers are:

1. National hydrographic offices for navigational warnings.
2. National weather services for meteorological warnings and forecasts.
3. Rescue Coordination Centers for ship-to-shore distress alerts and other urgent information.
4. In the U.S., the International Ice Patrol for North Atlantic ice hazards.

Each information provider prepares their SafetyNET messages with certain characteristics recognized by the EGC service. These characteristics, known as "C" codes are combined into a generalized message header format as follows: C1:C2:C3:C4:C5. Each "C" code controls a different broadcast criterion and is assigned a numerical value according to available options. A sixth "C" code, "C0" may be used to indicate the ocean region (i.e., AOR-E, AOR-W, POR, IOR) when sending a message to an LES which operates in more than one ocean region. Because errors in the header format of a message may prevent its being released, MSI providers must install an INMARSAT SafetyNET receiver to monitor the broadcasts it originates. This also ensures quality control.

The "C" codes are transparent to the mariner but are used by information providers to identify various transmitting parameters. C1 designates the message priority from distress to urgent, safety, and routine. MSI messages will always be at least at the safety level. C2 is the service code or type of message (for example, long range NAVAREA warning or coastal NAVTEX warning). It also tells the receiver the length of the address (the C3 code) it will need to decode. C3 is the address code. It can be the two digit code for the NAVAREA number for instance, or a 10 digit number to indicate a circular area for a meteorological warning. C4 is the repetition code which instructs the LES in how long and when to send the message to the NCS for actual broadcast. A six minute echo (repeat) may also be used to ensure that an urgent (unscheduled) message has been received by all ships affected. C5 is a constant and represents a presentation code, International Alphabet number 5, "00".

Broadcasts of MSI in the international SafetyNET service are in English.

2805. NAVTEX

NAVTEX is a maritime radio warning system consisting of a series of coast stations transmitting radio teletype (standard narrow-band direct printing, also sometimes called **Sitor**) safety messages on the internationally standard medium frequency of 518 kHz. It is a GMDSS requirement for the reception of MSI in coastal and local waters. Coast stations transmit during previously arranged time slots to minimize mutual interference. Routine messages are normally broadcast four times daily. Urgent messages are broadcast upon receipt, provided that an adjacent station is not transmitting. Since the broadcast uses the medium frequency band, a typical station service radius ranges from 100 to 500 NM day and night (although a 200 mile rule of thumb is applied in the U.S.). Interference from or receipt of stations farther away occasionally occurs at night.

Each NAVTEX message broadcast contains a four-character header describing: identification of station (first character); message content or type (second character); and message serial number (third and fourth characters). This header allows the microprocessor in the shipboard receiver to screen messages from only those stations relevant to the user, messages of subject categories needed by the user and messages not previously received by the user. Messages so screened are printed as they are received, to be read by the mariner when convenient. All other messages are suppressed. Suppression of unwanted messages is becoming more and more a necessity to the mariner as the number of messages, including rebroadcast messages, increases yearly. With NAVTEX, a mariner will not find it necessary to listen to, or sift through, a large number of non-relevant data to obtain the information necessary for safe navigation.

The NAVTEX receiver is a small unit with an internal printer, which takes a minimum of room on the bridge. Its antenna is also of modest size, needing only a receive capability.

2806. Maritime Safety Information (MSI)

Major categories of MSI for both NAVTEX and SafetyNET are:

1. Navigational warnings
2. Meteorological warnings
3. Ice reports
4. Search and rescue information
5. Meteorological forecasts
6. Pilot service messages (not in the U.S.)
7. Electronic navigation system messages (i.e., OMEGA, LORAN, DECCA, GPS, DGPS, SATNAV, etc.)

Broadcasts of MSI in NAVTEX international service are in English, but may be in languages other than English, to meet requirements of the host government.

2807. Digital Selective Calling (DSC)

Digital Selective Calling (DSC) is a method of auto-

matically placing a call directly from one radio to another. This is accomplished by addressing the call so it will be received automatically by the other radio. It permits a radio to be used like a telephone. Since the DSC system will sound an alarm (much like a ringing telephone) when it senses an incoming call, there is no need for dedicated, aural watchstanding. DSC techniques can be used with VHF, HF and MF radio communications. DSC's principal uses are in distress alerting and safety calling. Numerous frequencies have been assigned. They are 2187.5 kHz in the MF band; 4207.5 kHz, 6312 kHz, 8414.5 kHz, 12577 kHz and 16804.5 kHz in the HF band; and 156.525 MHz (channel 70) in the VHF band.

2808. Emergency Position-Indicating Radio Beacons

Emergency Position-Indicating Radio Beacons (EPIRBs) are designed to transmit a satellite alert in the event of sudden accident either automatically or manually. The automatic models are designed and mounted so that they will float free of a sinking vessel and be activated by seawater. The manual ones are controlled by a switch. Under GMDSS, satellite EPIRBs will operate either on 1.6 GHz (the INMARSAT E, L Band) or the 406 MHz frequency used by the COSPAS-SARSAT system.

GMDSS requires 1 satellite EPIRB along with 2 search and rescue transponders (SART's). These SART's generate a series of response signals when interrogated by any ordinary 9 GHz radar set. The signals produce a line of 20 blips on the radar screen of the rescue ship or aircraft.

Under GMDSS, the COSPAS-SARSAT and INMARSAT communication systems are the two basic media through which the EPIRB signal is relayed to ground and sea stations. COSPAS-SARSAT is a joint international satellite-aided SAR system operated by multi-national organizations in Canada, France, the U.S. and the Russian Federation. It uses low polar orbiting satellites which receive and relay distress signals from EPIRBs and determine their position. INMARSAT, with over 75 member nations, operates a global satellite EPIRB system (excluding the poles). Further details of the COSPAS-SARSAT system are found in Chapter 29, Position Reporting Systems.

CHAPTER 29

POSITION REPORTING SYSTEMS

INTRODUCTION

2900. Purpose

The purpose of position reporting systems is to monitor vessel positions and inform authorities and other vessels of an emergency or distress at sea so that a response can be coordinated among those best able to help. It is important that distress information be immediately available to Search and Rescue (SAR) coordinators so that assistance can be obtained with the least delay. Establishing communications is sometimes difficult even when automatic alarms are used, and determination of SAR capabilities and intentions of vessels is time-consuming, unless the essential information has been made readily available beforehand by their participation in a position reporting system.

The Convention on Safety of Life at Sea (SOLAS) obligates the master of any vessel who becomes aware of a distress incident to proceed to the emergency and assist until other aid is at hand or until released by the distressed vessel. Other international treaties and conventions impose the same requirement. Position reporting systems permit determination of the most appropriate early assistance, provide the means for a timely resolution of distress cases, and enable vessels responding to distress calls to continue their passage with a minimum amount of delay.

Other resolutions recommend that governments encourage participation in position reporting schemes by ensuring that no costs are incurred by the vessel for participation.

There are currently many position reporting systems in operation throughout the world. The particulars of each system are given in publications of the International Maritime Organization (IMO). Masters of vessels making offshore passages are requested by the U.S. Coast Guard to always participate in the AMVER System and to participate in the other systems when in the areas covered by them.

AMVER

2901. The Automated Mutual-Assistance Vessel Rescue System (AMVER)

AMVER, operated by the United States Coast Guard, is an international maritime mutual assistance program which assists search and rescue efforts in many offshore areas of the world. Merchant ships of all nations making offshore passages are encouraged to send movement (sailing) reports and periodic position reports voluntarily to the AMVER Center in New York via selected radio stations. Information from these reports is entered into a computer which maintains dead reckoning positions for the vessels.

Information concerning the predicted location and SAR characteristics of each vessel is available upon request to recognized SAR agencies of any nation or to vessels needing assistance. Predicted locations are disclosed only for reasons related to marine safety.

Messages sent within the AMVER System are at no cost to the ship or owner. Benefits to shipping include: (1) improved chances of aid in emergencies, (2) reduced number of calls for assistance to vessels not favorably located, and (3) reduced time lost for vessels responding to calls for assistance. An AMVER participant is under no greater obligation to render assistance during an emergency than a non-participating vessel.

All AMVER messages are addressed to Coast Guard, New York, regardless of the station to which the message is delivered, except those sent to Canadian stations which should be addressed to AMVER Halifax or AMVER Vancouver. This avoids incurring charges to the vessel.

In addition to the information calculated from sailing plans and position reports, the AMVER Center stores data on the characteristics of vessels. This includes the following: vessel name; international call sign; nation of registry; owner or operator; type of rig; type of propulsion; gross tonnage; length; normal cruising speed; radio schedule; radio facilities; radio telephone installed; surface search radar installed; doctor normally carried. Vessels can assist the AMVER Center in keeping this data accurate by sending a complete report by message, letter, or by completing a SAR Information Questionnaire available from AMVER, and sending corrections as the characteristics change. Corrections may be included in regular AMVER reports as remarks.

For AMVER participants bound for U.S. ports there is an additional benefit. AMVER messages which include the necessary information are considered to meet the requirements of 33 CFR 161 (Notice of arrival).

2902. AMVER System Communications Network

An extensive radio network supports the AMVER system. Propagation conditions, location of vessel, and message density will normally determine which station should be contacted to establish communications. To ensure that no charge is applied, all AMVER messages should be passed through specified radio

stations. Those which currently accept AMVER messages and apply to coastal station, ship station, or landline charge are listed in each issue of the AMVER Bulletin, together with respective call sign, location, frequency bands, and hours of guard. Although AMVER messages may be sent through other stations, the Coast Guard cannot reimburse the sender for any charges.

2903. The AMVER Bulletin

The **AMVER Bulletin**, published quarterly by the U.S. Coast Guard, provides information on the operation of the AMVER System of general interest to the mariner. It also provides up-to-date information on the AMVER communications network and Radio Wave Propagation Charts which indicate recommended frequencies for contacting U.S. coast radio stations participating in the AMVER System, according to the time of day and the season of the year.

2904. AMVER Participation

Instructions guiding participation in the AMVER System are available in the following languages: Chinese, Danish, Dutch, English, French, German, Greek, Italian, Japanese, Korean, Norwegian, Polish, Portuguese, Russian, Spanish and Swedish. The AMVER Users Manual is available from: Commander, Atlantic Area, U.S. Coast Guard, Governors Island, NY, 10004; Commander Pacific Area, U.S. Coast Guard, Government Island, Alameda, CA 94501; and at U.S. Coast Guard District Offices, Marine Safety Offices, Marine Inspection Offices and Captain of the Port Offices in major U.S. ports. Requests for instructions should state the language desired if other than English.

Search and Rescue operation procedures are contained in the *Merchant Ship Search and Rescue Manual* (MERSAR) published by the International Maritime Organization (IMO). U.S. flag vessels may obtain a copy of MERSAR from local Coast Guard Marine Safety Offices and Marine Inspection Offices or by writing to U.S. Coast Guard (G-OSR), Washington, DC 20593. Other flag vessels may purchase MERSAR directly from IMO.

In connection with a vessel's first AMVER-plotted voyage, the master is requested to complete a questionnaire providing the radio watch schedule, available medical and communications facilities, and other useful characteristics. Stored in the AMVER computer, this information can be electronically processed in an emergency, while a position is calculated.

Any vessel of any nation departing on an offshore passage of 24 hours duration or greater is encouraged to become a participant in the AMVER System by sending appropriate AMVER messages in one of several formats. The messages may be transmitted at any convenient time as long as the information is accurate.

There are five types of AMVER Reports.

1. Sailing Plan.
2. Departure Report.
3. Arrival Report.
4. Position Report.
5. Deviation Reports.

AMVER permits sailing plan and departure information to be combined into a single report. It also accepts sailing plan information separately.

Only the above five types of AMVER messages require specific formats. (See DMAHTC *Pub. 117, Radio Navigational Aids*). Other messages relating to a vessel's AMVER participation or data, such as facts on her SAR capabilities, may also be sent via the AMVER communications network.

Additional information concerning the AMVER System may be obtained by writing to: Commandant, U.S. Coast Guard, Washington, DC 20590, or by writing or visiting Commander, Atlantic Area, U.S. Coast Guard, Governors Island, New York, NY 10004. The AMVER System in the Pacific is coordinated by Commander, Pacific Area, U.S. Coast Guard, Government Island, Alameda, CA 94501.

Other countries such as Canada are a formal part of the AMVER System and provide radio stations for relay of AMVER reports, as well as coordinating rescue efforts in certain regions. Applicable instructions have been promulgated by official publications of the participating countries.

2905. AMVER Reporting Required

The U.S. Maritime Administration regulations state that certain U.S. flag vessels and foreign flag "War Risk" vessels must report and regularly update their voyages to the AMVER Center. This reporting is required of the following: (a) U.S. flag vessels of 1,000 tons or greater, operating in foreign commerce; (b) foreign flag vessels of 1,000 gross tons or greater, for which an Interim War Risk Insurance Binder has been issued under the provisions of Title XII, Merchant Marine Act, 1936.

2906. AMVER Plot Information

The information stored in the computer can be used to provide several types of display according to the needs of controllers at Rescue Coordination Centers. The surface picture (SURPIC) can be displayed as a **Radius SURPIC** (Figure 2906a). When requesting a Radius SURPIC, the controller specifies the date and time, a latitude and longitude to mark the center (P), the radius (in nautical miles) that the SURPIC should cover (R), and whether the names of all ships are desired (or only those with doctors, or perhaps those heading either east or west).

A Radius SURPIC may be requested for any radius from 1 to 999 miles. A sample request is as follows:

"REQUEST 062100Z RADIUS SURPIC OF DOCTORSHIPS WITHIN 800 MILES OF 43.6N 030.2W FOR MEDICAL EVALUATION M/V SEVEN SEAS."

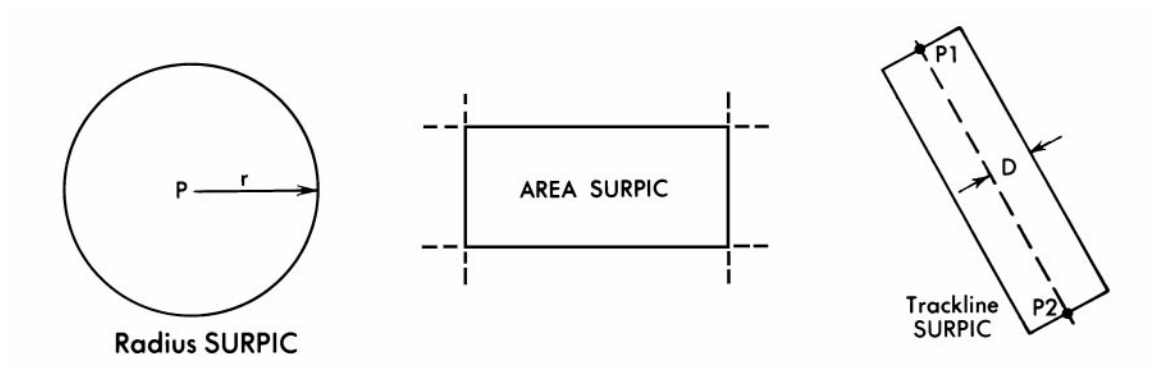


Figure 2906a. Radius SURPIC, Area SURPIC, and Trackine SURPIC.

The **Area SURPIC** is obtained by specifying the date, time, and two latitudes and two longitudes. The controller can limit the ships to be listed as with the Radius SURPIC. There is no maximum or minimum size limitation on an Area SURPIC.

A sample Area SURPIC request is as follows:

"REQUEST 151300Z AREA SURPIC OF WESTBOUND SHIPS FROM 43N TO 31N LATITUDE AND FROM 130W TO 150W LONGITUDE FOR SHIP DISTRESS M/V EVENING SUN LOCATION 37N, 140W."

The **Trackline SURPIC** is obtained by specifying the date and time, two points (P1 and P2), whether the trackline should be rhumb line or great circle, what the half-width (D) coverage should be (in nautical miles), and whether all ships are desired (or only doctor ships, or just those east or westbound). The half-width (D) specified should not exceed 100 miles. When received, the SURPIC will list ships in order from P1 to P2. There is no maximum or minimum distance between P1 and P2.

A sample Trackline SURPIC request is as follows:

"REQUEST 310100Z GREAT CIRCLE TRACKLINE SURPIC OF ALL SHIPS WITHIN 50 MILES OF A LINE FROM 20.1N 150.2W TO 21.5N 158.0W FOR AIRCRAFT PRECAUTION."

A **Location Vessel** is used to determine the location of a specific ship. It permits a controller to determine the DR position of an AMVER participant wherever located.

A sample Location Vessel request is as follows:

"REQUEST PRESENT POSITION, COURSE, AND SPEED OF M/V POLARIS"

A Radius SURPIC as it would be received by a rescue center, listing all ships within a 200-mile radius of 26.2N, 179.9W, is shown in figure 2906b.

2907. Uses Of AMVER Plot Information

An example of the use of a Radius SURPIC is depicted in Figure 2907. In this situation rescue authorities believe that a ship in distress, or her survivors, will be found in the rectangular area. The Rescue Coordination Center requests a listing of all eastbound ships within 100 miles of a carefully chosen position. Once this list is received by the Rescue Coordination Center a few moments later, messages can be prepared for satellite transmission to each vessel, or arrangements made to contact them by radio.

Each ship contacted may be asked to sail a rhumb line between two specified points, one at the beginning of the search area and one at the end. By carefully assigning ships to areas of needed coverage, very little time need be lost from the sailing schedule of each cooperating ship. Those ships joining the search would report their positions every few hours to the Rescue Coordination Center, together with weather data and any significant sightings. In order to achieve saturation coverage, a westbound SURPIC at the

Name	*Call sign*	Position	Course	Speed	SAR data	*Destination and ETA*	
CHILE MARU	JAYU	26.2 N 179.9E	C294	12.5K	H 1 6 R T X Z	KOBE	11
CPA 258 DEG. 012 MI. 032000Z							
WILYAMA	LKBD	24.8N 179.1W	C106	14.0K	H X R T V X Z	BALBOA	21
CPA 152 DEG. 092 MI. 032000Z							
PRES CLEVELAND	WITM	25.5N 177.0W	C284	19.3K	H 2 4 R D T X Z S	YKHAMA	08
CPA 265 WILL PASS WITHIN 10 MI 040430Z							
AENEAS	GMRT	25.9N 176.9E	C285	16.0K	H 8 R N V X Z	YKHAMA	10
CPA 265 DEG. 175 MI. 03200Z							

Figure 2906b. Radius SURPIC as received by a rescue center.

eastern extremity of the search area would also be used.

The Trackline SURPIC is most commonly used as a precautionary measure for aircraft. Rarely, if ever, is a major airliner forced to ditch at sea anymore. But occasions sometimes arise where a plane loses of one or more of its engines. A Trackline SURPIC, provided from the point of difficulty to the destination, provides the pilot with the added assurance of knowing the positions of vessels beneath him and that they have been alerted. SURPIC's have been used successfully to save the lives of pilots of small aircraft.

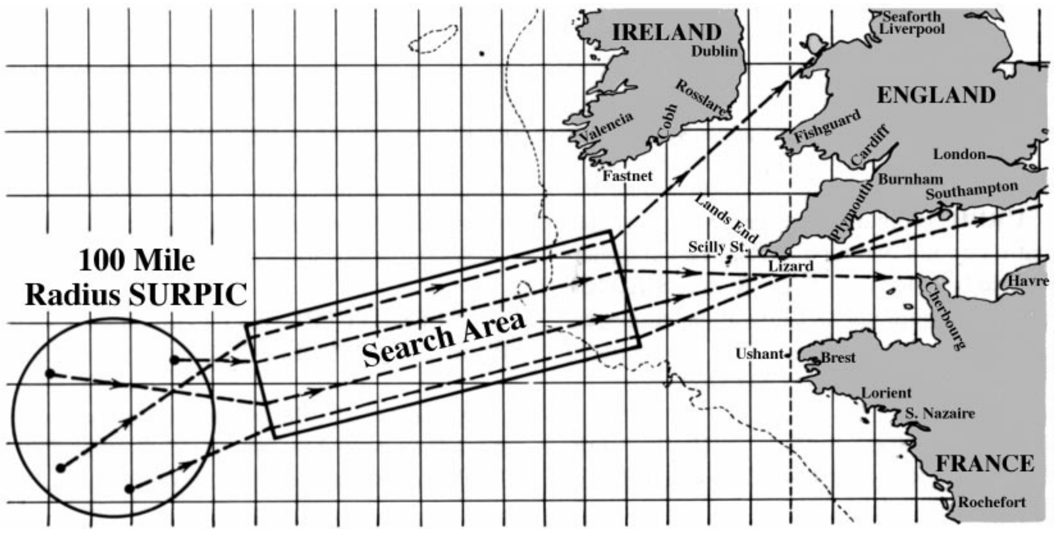


Figure 2907. Use of radius SURPIC.

EMERGENCY POSITION INDICATING RADIOBEACONS (EPIRB'S)

2908. Description And Capabilities

Emergency Position Indicating Radiobeacons (EPIRB's), devices which cost from $200 to over $1500, are designed to save lives by automatically alerting rescue authorities and indicating the distress location. EPIRB types are described below:

121.5/243 MHz EPIRB's (Class A, B, S): These are the most common and least expensive type of EPIRB, designed to be detected by overflying commercial or military aircraft. Satellites were designed to detect these EPIRB's but are limited for the following reasons:

1. Satellite detection range is limited for these EPIRB's (satellites must be within line of sight of both the EPIRB and a ground terminal for detection to occur).
2. EPIRB design and frequency congestion cause them to be subject to a high false alert/false alarm rate (over 99%); consequently, confirmation is re-

Type	Frequency	Description
Class A	121.5/243 MHz	Float-free, automatic activating, detectable by aircraft and satellite. Coverage limited (see Figure 2908).
Class B	121.5/243 MHz	Manually activated version of Class A.
Class C	VHF Ch. 15/16	Manually activated, operates on maritime channels only. Not detectable by satellite.
Class S	121.5/243 MHz	Similar to Class B, except that it floats, or is an integral part of a survival craft.
Category I	121.5/406 MHz	Float-free, automatically activated. Detectable by satellite anywhere in the world.
Category II	121.5/406 MHz	Similar to Category I, except manually activated.

Figure 2908a. EPIRB classifications.

Feature	*121.5/406 MHz EPIRB*	*121.5/243 MHz EPIRB*
Frequencies	406.025 MHz (locating) 121.500 MHz (homing)	121.500 MHz (civilian) 243.000 MHz (military)
Primary Function	Satellite alerting, locating, identification of distressed vessels.	Transmission of distress signal to passing aircraft and ships.
Distress Confirmation	Positive identification of coded beacon; each beacon signal is a coded, unique signal with registration data (vessel name, description, and telephone number ashore, assisting in confirmation).	Virtually impossible; no coded information, beacons often incompatible with satellites; impossible to know if signals are from EPIRB, ELT, or non-beacon source.
Signal	Pulse digital, providing accurate beacon location and vital information on distressed vessel.	Continuous signal allows satellite locating at reduced accuracy; close range homing.
Signal Quality	Excellent; exclusive use of 406 MHz for distress beacons; no problems with false alerts from non-beacon sources.	Relatively poor; high number of false alarms caused by other transmitters in the 121.5 MHz band.
Satellite Coverage	Global coverage, worldwide detection; satellite retains beacon data until next earth station comes into view.	Both beacon and LUT must be within coverage of satellite; detection limited to line of sight.
Operational Time	48 hrs. at -20°C.	48 hrs. at -20°C.
Output Power	5 watts at 406 MHz, .025 watts at 121.5 MHz.	0.1 watts average.
Strobe Light	High intensity strobe helps in visually locating search target.	None.
Location Accuracy (Search Area) and Time Required	1 to 3 miles (10.8 sq. miles); accurate position on first satellite overflight enables rapid SAR response, often within 30 min.	10 to 20 miles (486 sq. miles); SAR forces must wait for second system alert to determine final position before responding (1 to 3 hr. delay).

Figure 2908b. Summary comparison of 121.5/406 MHz and 121.5/243 MHz EPIRB's.

quired before SAR forces can be deployed;

3. EPIRB's manufactured before October 1988 may have design or construction problems (e.g. some models will leak and cease operating when immersed in water) or may not be detectable by satellite.

Class C EPIRB's: These are manually activated devices intended for pleasure craft which do not venture far offshore, and for vessels on the Great Lakes. They transmit a short burst on VHF-FM 156.8 MHz (Ch. 16) and a longer homing signal on 156.75 MHz (Ch. 15). Their usefulness depends upon a coast station or another vessel guarding channel 16 and recognizing the brief, recurring tone as an EPIRB. Class C EPIRB's are not recognized outside of the United States. Class C EPIRB's cannot be manufactured or sold in the United States after February 1995. Class C EPIRB's installed on board vessel's prior to February 1995 may be utilized until 1 February 1999 and not thereafter.

406 MHz EPIRB's (Category I, II): The 406 MHz EPIRB was designed to operate with satellites. Its signal allows a satellite local user terminal to locate the EPIRB (much more accurately than 121.5/243 MHz devices) and identify the vessel (the signal is encoded with the vessel's identity) anywhere in the world. There is no range limitation. These devices also include a 121.5 MHz homing signal, allowing aircraft and rescue vessels to quickly find the vessel in distress. These are the only type of EPIRB which must be tested by Coast Guard-approved independent laboratories before they can be sold for use within the United States.

An automatically activated, float-free version of this EPIRB has been required on SOLAS vessels (cargo ships over 300 tons and passenger ships on international voyages) since 1 August 1993. The Coast Guard requires U.S. commercial fishing vessels to carry this device (unless they carry a Class A EPIRB), and will require the same for other U.S. commercial uninspected vessels which travel more than 3 miles offshore.

Mariners should be aware of the differences between capabilities of 121.5/243 MHz and 121.5/406 MHz EPIRB's, as they have implications for alerting and locating of distress sites, as well as response by SAR forces. The advantages of 121.5/406 MHz devices are substantial, and are further enhanced by EPIRB-transmitted registration data on the carrying vessel. Owners of 121.5/406 MHz EPIRB's furnish registration information about their vessel, survival gear, and emergency points of contact ashore, all of which greatly enhance the response. The database for U.S. vessels is maintained by the National Oceanographic and Atmospheric Administration, and is accessed worldwide by SAR authorities to facilitate SAR response.

2909. Testing EPIRB's

EPIRB owners should periodically check for water tightness, battery expiration date, and signal presence. FCC rules allow Class A, B, and S EPIRB's to be turned on briefly (for three audio sweeps, or 1 second only) during the first 5 minutes of any hour. Signal presence can be detected by an FM radio tuned to 99.5 MHz, or an AM radio tuned to any vacant frequency and located close to an EPIRB. FCC rules allow Class C EPIRB's to be tested within the first 5 minutes of any hour, for not more than 10 seconds. Class C EPIRB's can be detected by a marine radio tuned to channel 15 or 16. All 121.5/406 MHz EPIRB's have a self-test function that should be used in accordance with manufacturers' instructions at least monthly.

2910. The COSPAS/SARSAT System

COSPAS is a Russian acronym for "Space System for Search of Distressed Vessels"; SARSAT signifies "Search And Rescue Satellite-Aided Tracking." COSPAS-SARSAT is an international satellite-based search and rescue system established by the U.S., Russia, Canada, and France to locate emergency radiobeacons transmitting on the frequencies 121.5, 243, and 406 MHz. Since its inception, the COSPAS-SARSAT system (SARSAT satellite only) has contributed to saving over 3000 lives.

The USCG receives data from MRCC stations and SAR Points of Contact (SPOC). See Figure 2910.

2911. Operation Of The COSPAS/SARSAT System

If an EPIRB is activated, COSPAS/SARSAT picks up the signal, locates the source and passes the information to a land station. From there, the information is relayed, either via coast radio or satellite, to Rescue Coordination Centers, rescue vessels and nearby ships. This constitutes a one-way only communications system, from the EPIRB via the satellite to the rescuers. It employs low altitude, near polar orbiting satellites and by exploiting the Doppler principle, locates the transmitting EPIRB within about two miles. Due to the low polar orbit, there may by a delay in receiving the distress message unless the footprint of the satellite is simultaneously in view with a monitoring station. However, unlike SafetyNET, worldwide coverage is provided.

As a satellite approaches a transmitting EPIRB, the frequency of the signals it receives is higher than that being transmitted; when the satellite has passed the EPIRB, the received frequency is lower. This creates a notable Doppler shift. Calculations which take into account the earth's rotation and other factors then determine the location of the EPIRB.

Country	*Location*	*Designator*	*Status*
Australia	Canberra	AUMCC	In Operation
Brazil	San Paulo	BBMCC	Under Test
Canada	Trenton	CMCC	In Operation
Chile	Santiago	CHMCC	Under Test
France	Toulouse	FMCC	In Operation
Hong Kong	Hong Kong	HKMCC	In Operation
India	Bangalore	INMCC	In Operation
Indonesia	Jakarta	IONCC	Under Test
ITDC	Taipei	TAMCC	TBD
Japan	Tokyo	JAMCC	In Operation
New Zealand			In Operation
Norway	Bodo	NMCC	In Operation
Pakistan	Lahore	PAMCC	—
Singapore	Singapore	SIMCC	—
Spain	Maspalomas	SPMCC	In Operation
Russian Federation	Moscow	CMC	In Operation
United Kingdom	Plymouth	UKMCC	In Operation
United States	Suitland	USMCC	In Operation

Figure 2910. Participants in COSPAS/SARSAT system.

The 406 MHz EPIRB’s incorporate an identification code. Once the satellite receives the beacon’s signals, the Doppler shift is measured and the beacon’s digital data is recovered from the signal. The information is time-lagged, formatted as digital data and transferred to the repeater downlink for real time transmission to any local user terminal. The digital data coded into each 406 MHz EPIRB’s memory provides distress information to SAR authorities for more rapid and efficient rescue. The data includes a maritime identification digit (MID, a 3 digit number identifying the administrative country) and either a ship station identifier (SSI, a 6 digit number assigned to specific ships), a ship radio call sign or a serial number to identify the ship in distress.

With the INMARSAT E satellite EPIRB’s, coverage does not extend to very high latitudes, but within the coverage area the satellite connection is instantaneous. However, to establish the EPIRB’s position, an interface with a GPS receiver or other sensor is needed.

2912. Alarm, Warning, And Alerting Signals

For MF (i.e. 2182 kHz), the EPIRB signal consists of either (1) a keyed emission modulated by a tone of 1280 Hz to 1320 Hz with alternating periods of emission and silence of 1 to 1.2 seconds each; or (2) the radiotelephone alarm signal followed by Morse code B (— • • •) and/or the call sign of the transmitting ship, sent by keying a carrier modulated by a tone of 1300 Hz or 2200 Hz. For VHF (i.e. 121.5 MHz and 243 MHz), the signal characteristics are in accordance with the specifications of Appendix 37A of the ITU Radio Regulations. For 156.525 MHz and UHF (i.e. 406 MHz to 406.1 MHz and 1645.5 MHz to 1646.5 MHz), the signal characteristics are in accordance with CCIR recommendations.

The purpose of these signals is to help determine the position of survivors for SAR operations. They indicate that one or more persons are in distress, may no longer be aboard a ship or aircraft, and may not have a receiver available.

Any vessel or aircraft receiving an EPIRB signal while no distress or urgent traffic is being passed shall initiate a distress message on the assumption that the EPIRB sending station is unable to transmit a distress message. The keying cycles for MF EPIRB’s may be interrupted for speech transmission.

CHAPTER 30

HYDROGRAPHY AND HYDROGRAPHIC REPORTS

3000. Introduction

Because the nautical chart is so essential to safe navigation, it is important for the mariner to understand the capabilities and limitations of both digital and paper charts. Previous chapters have dealt with horizontal and vertical datums, chart projections, and other elements of cartographic science. This chapter will explain some basic concepts of hydrography and cartography which are important to the navigator, both as a user and as a source of data. **Hydrography** is the science of measurement and description of all of the factors which affect navigation, including depths, shorelines, tides, currents, magnetism, and other factors. **Cartography** is the final step in a long process which leads from raw data to a usable chart for the mariner.

The mariner, in addition to being the primary user of hydrographic data, is also an important source of data used in the production and correction of nautical charts. This chapter discusses the processes involved in producing a nautical chart, whether in digital or paper form, from the initial planning of a hydrographic survey to the final printing. With this information, the mariner can better evaluate the information which comes to his attention and can forward it in a form that will be most useful to charting agencies, allowing them to produce more accurate and useful charts.

BASICS OF HYDROGRAPHIC SURVEYING

3001. Planning The Survey

The basic documents used to produce nautical charts are hydrographic surveys. Much additional information is included, but the survey is central to the compilation of a chart. A survey begins long before actual data collection starts. Some elements which must be decided are:

- Exact area of the survey.
- Type of survey (reconnaissance or standard) and scale to meet standards of chart to be produced.
- Scope of the survey (short or long term).
- Platforms available (ships, launches, aircraft, leased vessels, cooperative agreements).
- Support work required (aerial or satellite photography, geodetics, tides).
- Limiting factors (budget, political or operational constraints, positioning systems limitations, logistics).

Once these issues are decided, all information available in the survey area is reviewed. This includes aerial photography, satellite data, topographic maps, existing nautical charts, geodetic information, tidal information, and anything else affecting the survey. The survey planners then compile sound velocity information, climatology, water clarity data, any past survey data, and information from lights lists, sailing directions, and notices to mariners. Tidal information is thoroughly reviewed and tide gauge locations chosen. Local vertical control data is reviewed to see if it meets the expected accuracy standards, so the tide gauges can be linked to the vertical datum used for the survey. Horizontal control is reviewed to check for accuracy and discrepancies and to determine sites for local positioning systems to be used in the survey.

Line spacing refers to the distance between tracks to be run by the survey vessel. It is chosen to provide the best coverage of the area using the equipment available. Line spacing is a function of the depth of water, the sound footprint of the collection equipment to be used, and the complexity of the bottom. Once line spacing is chosen, the hydrographer can compute the total miles of survey track to be run and have an idea of the time required for the survey, factoring in the expected weather and other possible delays. The scale of the survey, orientation to the shorelines in the area, and the method of positioning determine line spacing. Planned tracks are laid out so that there will be no gaps between sound lines and sufficient overlaps between individual survey areas.

Lines with spacing greater than the primary survey's line spacing are run at right angles to the primary survey development to verify data repeatability. These are called **cross check lines**.

Other tasks to be completed with the survey include bottom sampling, seabed coring, production of sonar pictures of the seabed, gravity and magnetic measurements (on deep ocean surveys), and sound velocity measurements in the water column.

3002. Echo Sounders In Hydrographic Surveying

Echo sounders were developed in the early 1920s, and compute the depth of water by measuring the time it takes for a pulse of sound to travel from the source to the sea bottom and return. A device called a **transducer** converts electrical energy into sound energy and vice versa. For basic hydrographic surveying, the transducer is mounted permanently in the bottom of the survey vessel, which then follows the planned trackline, generating soundings along the track.

The major difference between different types of echo sounders is in the frequencies they use. Transducers can be classified according to their beam width, frequency, and power rating. The sound radiates from the transducer in a cone, with about 50% actually reaching to sea bottom. **Beam width** is determined by the frequency of the pulse and the size of the transducer. In general, lower frequencies produce a wider beam, and at a given frequency, a smaller transducer will produce a wider beam. Lower frequencies also penetrate deeper into the water, but have less resolution in depth. Higher frequencies have greater resolution in depth, but less range, so the choice is a trade-off. Higher frequencies also require a smaller transducer. A typical low frequency transducer operates at 12 kHz and a high frequency one at 200 kHz.

The formula for depth determined by an echo sounder is:

$$D = \frac{V \times T}{2} + K + D_r$$

where D is depth from the water surface, V is the average velocity of sound in the water column, T is round-trip time for the pulse, K is the system index constant, and D_r is the depth of the transducer below the surface (which may not be the same as vessel draft). V, D_r, and T can be only generally determined, and K must be determined from periodic calibration. In addition, T depends on the distinctiveness of the echo, which may vary according to whether the sea bottom is hard or soft. V will vary according to the density of the water, which is determined by salinity, temperature, and pressure, and may vary both in terms of area and time. In practice, average sound velocity is usually measured on site and the same value used for an entire survey unless variations in water mass are expected. Such variations could occur, for example, in areas of major currents. While V is a vital factor in deep water surveys, it is normal practice to reflect the echo sounder signal off a plate suspended under the ship at typical depths for the survey areas in shallow waters. The K parameter, or index constant, refers to electrical or mechanical delays in the circuitry, and also contains any constant correction due to the change in sound velocity between the upper layers of water and the average used for the whole project. Further, vessel speed is factored in and corrections are computed for settlement and squat, which affect transducer depth. Vessel roll, pitch, and heave are also accounted for. Finally, the observed tidal data is recorded in order to correct the soundings during processing.

Tides are accurately measured during the entire survey so that all soundings can be corrected for tide height and thus reduced to the chosen vertical datum. Tide corrections eliminate the effect of the tides on the charted waters and ensure that the soundings portrayed on the chart are the minimum available to the mariner at the sounding datum. Observed, not predicted, tides are used to account for both astronomically and meteorlogically induced water level changes during the survey.

3003. Collecting Survey Data

While sounding data is being collected along the planned tracklines by the survey vessel(s), a variety of other related activities are taking place. A large-scale **boat sheet** is produced with many thousands of individual soundings plotted. A complete navigation journal is kept of the survey vessel's position, course and speed. Side-scan sonar may be deployed to investigate individual features and identify rocks, wrecks, and other dangers. Time is the parameter which links the ship's position with the various echograms, sonograms, journals, and boat sheets that make up the hydrographic data package.

3004. Processing Hydrographic Data

During processing, echogram data and navigational data are combined with tidal data and vessel/equipment corrections to produce **reduced soundings**. This reduced data is combined on a plot of the vessel's actual track the boat sheet data to produce a **smooth sheet**. A contour overlay is usually made to test the logic of all the data shown. All anomolous depths are rechecked in either the survey records or in the field. If necessary, sonar data are then overlayed to analyze individual features as related to depths. It may take dozens of smooth sheets to cover the area of a complete survey. The smooth sheets are then ready for cartographers, who will choose representative soundings manually or using automated systems from thousands shown, to produce a nautical chart. Documentation of the process is such that any individual sounding on any chart can be traced back to its original uncorrected value. See Figure 3004.

3005. Recent Developments In Hydrographic Surveying

The evolution of echo sounders has followed the same pattern of technological innovation seen in other areas. In the 1940s low frequency/wide beam sounders were developed for ships to cover larger ocean areas in less time with some loss of resolution. Boats used smaller sounders which usually required visual monitoring of the depth. Later, narrow beam sounders gave ship systems better resolution using higher frequencies, but with a corresponding loss of area. These were then combined into dual-frequency systems. All echo sounders, however, used a single transducer, which limited surveys to single lines of soundings. For boat equipment, automatic recording became standard.

The last three decades have seen the development of multi-

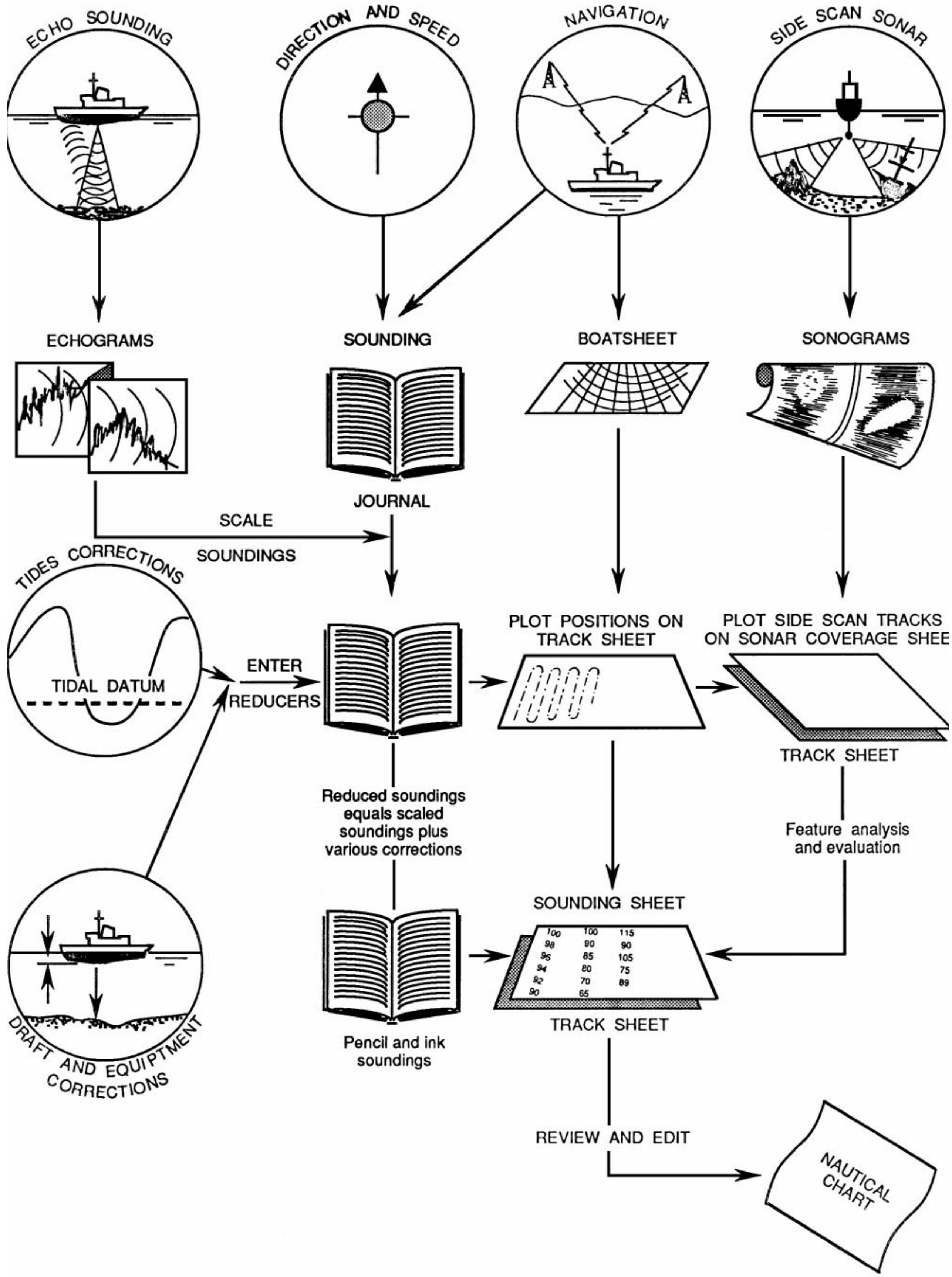


Figure 3004. The process of hydrographic surveying.

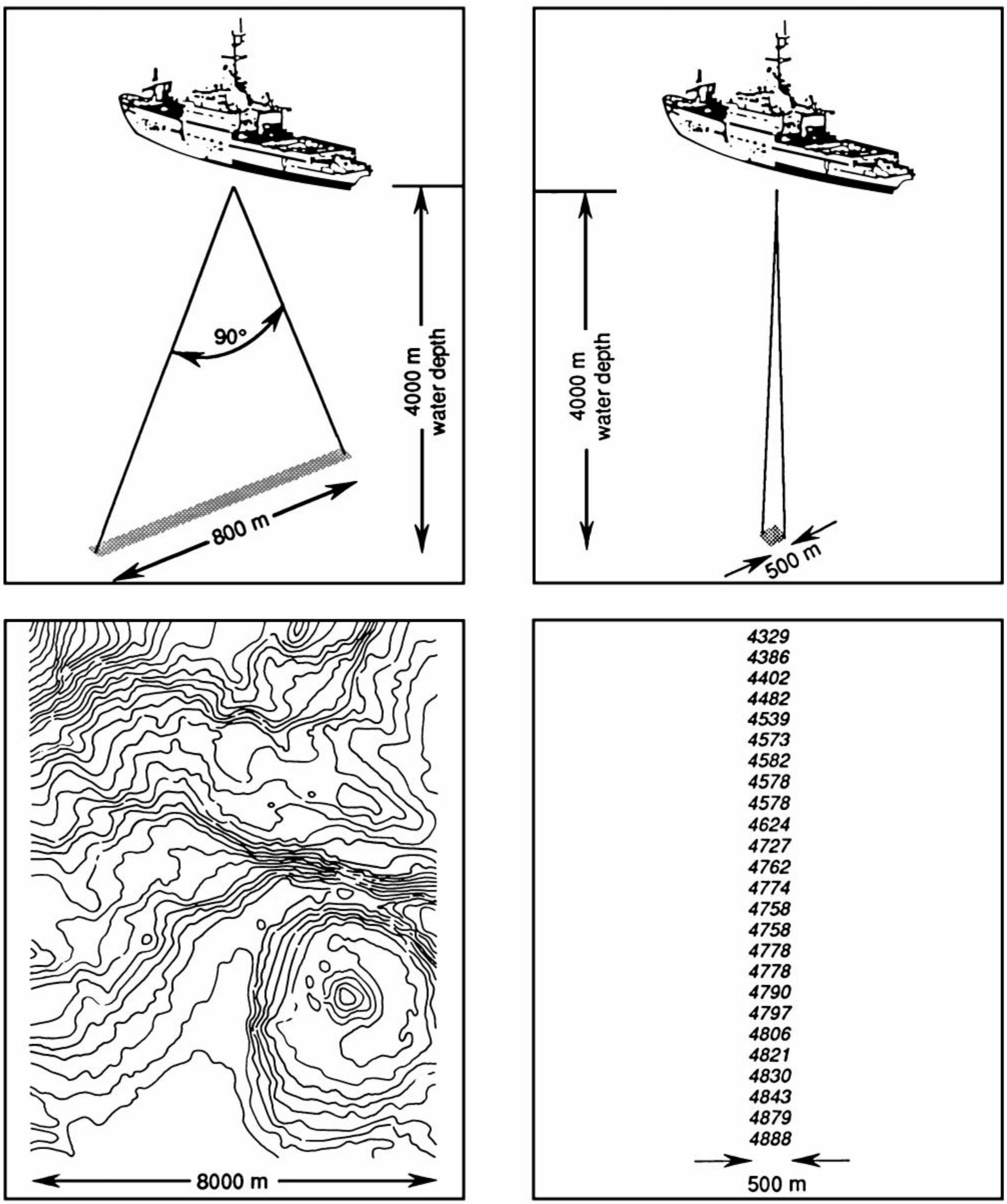


Figure 3005. Swath versus single-transducer surveys.

ple-transducer, multiple-frequency sounding systems which are able to scan a wide area of seabed. Two general types are in use. Open waters are best surveyed using an array of transducers spread out athwartships across the hull of the survey vessel. They may also be deployed from an array towed behind the vessel at some depth to eliminate corrections for vessel heave, roll, and pitch. Typically, as many as 16 separate transducers are arrayed, sweeping an arc of 90°. The area covered by these **swath survey systems** is thus a function of water depth. In shallow water, track lines must be much closer together than in deep water. This is fine with hydrographers, because shallow waters need more closely spaced data to provide an accurate portrayal of the bottom on charts. The second type of multiple beam system uses an array of vertical beam transducers rigged out on poles abeam the survey vessel with transducers spaced to give overlapping coverage for the general water depth. This is an excellent configuration for very shallow water, providing very densely spaced soundings from which an accurate picture of the bottom can be made for harbor and small craft charts. The width of the swath of this system is fixed by the distance between the two outermost transducers and is not dependent on water depth.

A recent development is **Airborne Laser Hydrography (ALH)**. An aircraft flies over the water, transmitting a laser beam. Part of the generated laser beam is reflected by the water's surface, which is noted by detectors. The rest penetrates to the sea bottom and is also partially reflected; this is also detected. Water depth can be computed from the difference in times of receipt of the two reflected pulses. Two different wavelength beams can also be used, one which reflects off the surface of the water, and one which penetrates and is reflected off the sea bottom. The obvious limitation of this system is water clarity. However, no other system can survey at 200 or so miles per hour while operating directly over shoals, rocks, reefs, and other hazards to boats. Both polar and many tropical waters are suitable for ALH systems. Depth readings up to 40 meters have been made, and at certain times of the year, some 80% of the world's coastal waters are estimated to be clear enough for ALH.

HYDROGRAPHIC REPORTS

3006. Chart Accuracies

The chart results from a hydrographic survey can be no more accurate than the survey; the survey's accuracy, in turn, is limited by the positioning system used. For many older charts, the positioning system controlling data collection involved using two sextants to measure horizontal angles between signals established ashore. The accuracy of this method, and to a lesser extent the accuracy of modern, shore based electronic positioning methods, deteriorates rapidly with distance. This often determined the maximum scale which could be considered for the final chart. With the advent of the Global Positioning System (GPS) and the establishment of Differential GPS networks, the mariner can now navigate with greater accuracy than could the hydrographic surveyor who collected the chart source data. Therefore, exercise care not to take shoal areas or other hazards closer aboard than was past practice because they may not be exactly where charted. This is in addition to the caution the mariner must exercise to be sure that his navigation system and chart are on the same datum. The potential danger to the mariner increases with digital charts because by zooming in, he can increase the chart scale beyond what can be supported by the source data. The constant and automatic update of the vessels position on the chart display can give the navigator a false sense of security, causing him to rely on the accuracy of a chart when the source data from which the chart was compiled cannot support the scale of the chart displayed.

3007. Navigational And Oceanographic Information

Mariners at sea, because of their professional skills and location, represent a unique data collection capability unobtainable by any government agency. Provision of high quality navigational and oceanographic information by government agencies *requires* active participation by mariners in data collection and reporting. Examples of the type of information required are reports of obstructions, shoals or hazards to navigation, sea ice, soundings, currents, geophysical phenomena such as magnetic disturbances and subsurface volcanic eruptions, and marine pollution. In addition, detailed reports of harbor conditions and facilities in both busy and out-of-the-way ports and harbors helps charting agencies keep their products current. The responsibility for collecting hydrographic data by U.S. Naval vessels is detailed in various directives and instructions. Civilian mariners, because they often travel to a wider range of ports, also have an opportunity to contribute substantial amounts of information.

3008. Responsibility For Information

The Defense Mapping Agency, the U.S. Naval Oceanographic Office (NAVOCEANO), the U.S. Coast Guard and the Coast and Geodetic Survey (C&GS) are the primary agencies which receive, process, and disseminate marine information in the U.S.

DMA provides charts and chart update (*Notice to Mariners*) and other nautical materials for the U.S. military services and for navigators in general in waters outside the U.S.

NAVOCEANO conducts hydrographic and oceanographic surveys of primarily foreign or international waters, and disseminates information to naval forces, government agencies, and civilians.

The Coast and Geodetic Survey (C&GS) conducts hydrographic and oceanographic surveys and provides charts for marine and air navigation in the coastal zones of the United States and its territories.

The U.S. Coast Guard is charged with protecting safety of life and property at sea, maintaining aids to navigation,

and improving the quality of the marine environment. In the execution of these duties, the Coast Guard collects, analyzes, and disseminates navigational and oceanographic data.

Modern technology allows contemporary navigators to contribute to the body of hydrographic and oceanographic information.

Navigational reports are divided into four categories:

1. Safety Reports
2. Sounding Reports
3. Marine Data Reports
4. Port Information Reports

The seas and coastlines continually change through the actions of man and nature. Improvements realized over the years in the nautical products published by DMAHTC, NOS, and U.S. Coast Guard have been made possible largely by the reports and constructive criticism of seagoing observers, both naval and merchant marine. DMAHTC and NOS continue to rely to a great extent on the personal observations of those who have seen the changes and can compare charts and publications with actual conditions. In addition, many ocean areas and a significant portion of the world's coastal waters have never been adequately surveyed for the purpose of producing modern nautical charts.

Information from all sources is evaluated and used in the production and maintenance of DMAHTC, NOS and Coast Guard charts and publications. Information from surveys, while originally accurate, is subject to continual change. As it is impossible for any hydrographic office to conduct continuous worldwide surveys, reports of changing conditions depend on the mariner. Such reports provide a steady flow of valuable information from all parts of the globe.

After careful analysis of a report and comparison with all other data concerning the same area or subject, the organization receiving the information takes appropriate action. If the report is of sufficient urgency to affect the immediate safety of navigation, the information will be broadcast as a SafetyNET or NAVTEX message. Each report is compared with others and contributes in the compilation, construction, or correction of charts and publications. It is only through the constant flow of new information that charts and publications can be kept accurate and up-to-date.

A convenient Data Collection Kit is available free from DMAHTC and NOS sales agents and from DMAHTC Representatives. The stock number is HYDRODATAKIT.

3009. Safety Reports

Safety reports are those involving navigational safety which must be reported and disseminated by message. The types of dangers to navigation which will be discussed in this section include ice, floating derelicts, wrecks, shoals, volcanic activity, mines, and other hazards to shipping.

1. Ice—Mariners encountering ice, icebergs, bergy bits, or growlers in the North Atlantic should report to Commander, International Ice Patrol, Groton, CT through a U.S. Coast Guard Communications Station. Direct printing radio teletype (SITOR) is available through USCG Communications Stations Boston or Portsmouth.

Satellite telephone calls may be made to the Ice Patroloffice in Groton, Connecticut throughout the season at (203) 441-2626 (Ice Patrol Duty Officer). Messages can also be sent through Coast Guard Operations Center, Boston at (617) 223-8555.

When sea ice is observed, the concentration, thickness, and position of the leading edge should be reported. The size, position, and, if observed, rate and direction of drift, along with the local weather and sea surface temperature, should be reported when icebergs, bergy bits, or growlers are encountered.

Ice sightings should also be included in the regular synoptic ship weather report, using the five-figure group following the indicator for ice. This will assure the widest distribution to all interested ships and persons. In addition, sea surface temperature and weather reports should be made to COMINTICEPAT every 6 hours by vessels within latitude 40°N and 52°N and longitude 38°W and 58°W, if a routine weather report is not made to METEO Washington.

2. Floating Derelicts—All observed floating and drifting dangers to navigation that could damage the hull or propellers of a vessel at sea should be immediately reported by radio. The report should include a brief description of the danger, the date, time (GMT) and the location (latitude and longitude).

3.Wrecks/Man-Made Obstructions—Information is needed to assure accurate charting of wrecks, man-made obstructions, other objects dangerous to surface and submerged navigation, and repeatable sonar contacts that may be of interest to the U.S. Navy. Man-made obstructions not in use or abandoned are particularly hazardous if unmarked and should be reported immediately. Examples include abandoned wellheads and pipelines, submerged platforms and pilings, and disused oil structures. Ship sinkings, strandings, disposals. or salvage data are also reportable, along with any large amounts of debris, particularly metallic.

Accuracy, especially in position, is vital: therefore, the date and time of the observation of the obstruction as well as the method used in establishing the position, and an estimate of the fix accuracy should be included. Reports should also include the depth of water, preferably measured by soundings (in fathoms or meters). If known, the name, tonnage, cargo, and cause of casualty should be provided.

Data concerning wrecks, man-made obstructions, other sunken objects, and any salvage work should be as complete as possible. Additional substantiating information is encouraged.

4. Shoals—When a vessel discovers an uncharted or erroneously charted shoal or an area that is dangerous to navigation, all essential details should be immediately reported to

DMAHTC WASHINGTON DC via radio. An uncharted depth of 300 fathoms or less is considered an urgent danger to submarine navigation. Immediately upon receipt of messages reporting dangers to navigation, DMAHTC issues appropriate NAVAREA warnings. The information must appear on published charts as "reported" until sufficient substantiating evidence (i.e. clear and properly annotated echograms and navigation logs, and any other supporting information) is received.

Therefore, originators of shoal reports are requested to verify and forward all substantiating evidence to DMAHTC at the earliest opportunity. It cannot be overemphasized that clear and properly annotated echograms and navigation logs are especially important in shoal reports.

5. Volcanic Activity—Volcanic disturbances may be observed from ships in many parts of the world. On occasion, volcanic eruptions may occur beneath the surface of the water. These submarine eruptions may occur more frequently and be more widespread than has been suspected in the past. Sometimes the only evidence of a submarine eruption is a noticeable discoloration of the water, a marked rise in sea surface temperature, or floating pumice. Mariners witnessing submarine activity have reported steams with a foul sulfurous odor rising from the sea surface, and strange sounds heard through the hull, including shocks resembling a sudden grounding. A subsea volcanic eruption may be accompanied by rumbling and hissing as hot lava meets the cold sea.

In some cases, reports of discolored water at the sea surface have been investigated and found to be the result of newly formed volcanic cones on the sea floor. These cones can grow rapidly (within a few years) to constitute a hazardous shoal.

It is imperative that a mariner report evidence of volcanic activity immediately to DMAHTC by message. Additional substantiating information is encouraged.

6. **Mines**—All mines or objects resembling mines should be considered armed and dangerous. An immediate radio report to DMAHTC should include (if possible):

1. Greenwich Mean Time and date.
2. Position of mine, and how near it was approached.
3. Size, shape, color, condition of paint, and presence of marine growth.
4. Presence or absence of horns or rings.
5. Certainty of identification.

3010. Instructions For Safety Report Messages

The International Convention for the Safety of Life at Sea (1974), which is applicable to all U.S. flag ships, requires: "The master of every ship which meets with dangerous ice, dangerous derelict, or any other direct danger to navigation, or a tropical storm, or encounters subfreezing air temperatures associated with gale force winds causing severe ice accretion on superstructures, or winds of force 10 or above on the Beaufort scale for which no storm warning has been received, is bound to communicate the information by all means at his disposal to ships in the vicinity, and also to the competent authorities at the first point on the coast with which he can communicate."

The report should be broadcast first on 2182 kHz prefixed by the safety signal "SECURITE." This should be followed by transmission of the message on a suitable working frequency to the proper shore authorities. The transmission of information regarding ice, derelicts, tropical storms, or any other direct danger to navigation is obligatory. The form in which the information is sent is not obligatory. It may be transmitted either in plain language (preferably English) or by any means of International Code of Signals (wireless telegraphy section). It should be issued CQ to all ships and should also be sent to the first station with which communication can be made with the request that it be transmitted to the appropriate authority. A vessel will not be charged for radio messages to government authorities reporting dangers to navigation.

Each radio report of a danger to navigation should answer briefly three questions:

1. What? A description to of the object or phenomenon.
2. Where? Latitude and longitude.
3. When? Greenwich Mean Time (GMT) and date.

Examples:

Ice

SECURITE. ICE: LARGE BERG SIGHTED DRIFTING SW AT .5 KT 4605N, 4410W, AT 0800 GMT, MAY 15.

Derelicts

SECURITE. DERELICT: OBSERVED WOODEN 25 METER DERELICT ALMOST SUBMERGED AT 4406N, 1243W AT 1530 GMT, APRIL 21.

The report should be addressed to one of the following shore authorities as appropriate:

1. U.S. Inland Waters—Commander of the Local Coast Guard District.
2. Outside U.S. Waters—DMAHTC WASHINGTON, DC.

Whenever possible, messages should be transmitted via the nearest government radio station. If it is impractical to use a government station, a commercial station may be used. U.S. government navigational warning messages should invariably be sent through U.S. radio stations, government or commercial, and never through foreign stations.

Detailed instructions for reporting via radio are contained in DMAHTC *Pub. 117, Radio Navigation Aids.*

OCEANIC SOUNDING REPORTS

3011. Sounding Reports

Acquisition of reliable sounding data from all ocean areas of the world is a continuing effort of DMAHTC, NAVOCEANO, and NOS. There are vast ocean areas where few soundings have ever been acquired. Much of the bathymetric data shown on charts has been compiled from information submitted by mariners. Continued cooperation in observing and submitting sounding data is absolutely necessary to enable the compilation of accurate charts. Compliance with sounding data collection procedures by merchant ships is voluntary, but for U.S. Naval vessels compliance is required under various fleet directives.

3012. Areas Where Soundings Are Needed

Prior to a voyage, navigators can determine the importance of recording sounding data by checking the charts for the route. Any ship crossing a densely sounded shipping lane perpendicular or nearly perpendicular to the lane can obtain very useful sounding data despite the density. Such tracks provide cross checks for verifying existing data. Other indications that soundings may be particularly useful are:

1. Old sources listed on source diagram or source note on chart.
2. Absence of soundings in large areas.
3. Presence of soundings, but only along well-defined lines indicating the track of the sounding vessel, with few or no sounding between tracks.
4. Legends such as “Unexplored area.”

3013. Fix Accuracy

A realistic goal of open ocean positioning for sounding reports is ±1 nautical mile with the continuous use of GPS. However, depths of 300 fathoms or less should always be reported regardless of the fix accuracy. When such depths are uncharted or erroneously charted, they should be reported by message to DMAHTC WASHINGTON DC, giving the best available positioning accuracy. Echograms and other supporting information should then be forwarded by mail to DMAHTC.

The accuracy goal noted above has been established to enable DMAHTC to create a high quality data base which will support the compilation of accurate nautical charts. It is particularly important that reports contain the navigator’s best estimate of his fix accuracy and that the positioning aids being used (GPS, Loran C, etc.) be identified.

3014. False Shoals

Many poorly identified shoals and banks shown on charts are probably based on encounters with the **Deep Scattering Layer (DSL)**, ambient noise, or, on rare occasions, submarine earthquakes. While each appears real enough at the time of its occurrence, a knowledge of the events that normally accompany these incidents may prevent erroneous data from becoming a charted feature.

The DSL is found in most parts of the world. It consists of a concentration of marine life which descends from near the surface at sunrise to an approximate depth of 200 fathoms during the day. It returns near the surface at sunset. Although at times the DSL may be so concentrated that it will completely mask the bottom, usually the bottom return can be identified at its normal depth at the same time the DSL is being recorded.

Ambient noise or interference from other sources can cause erroneous data. This interference may come from equipment on board the ship, from another transducer being operated close by, or from waterborne noise. Most of these returns can be readily identified on the echo sounder records and should cause no major problems; however, on occasion they may be so strong and consistent as to appear as the true bottom.

Finally, a volcanic disturbance beneath the ship or in the immediate vicinity may give erroneous indications of a shoal. The experience has at times been described as similar to running aground or striking a submerged object. Regardless of whether the feature is an actual shoal or a submarine eruption the positions, date/time, and other information should be promptly reported to DMAHTC.

3015. Doubtful Hydrographic Data

Navigators are strongly requested to assist with the confirmation and proper charting of actual shoals and the removal from the charts of doubtful data which was erroneously reported.

The classification or confidence level assigned to doubtful hydrographic data is indicated by the following standard symbols:

Abbreviation	*Meaning*
Rep (date)	Reported (year)
E.D.	Existence Doubtful
P.A.	Position Approximate
P.D.	Position Doubtful

Many of these reported features are sufficiently deep that if valid, a ship can safely navigate across the area. Confirmation of the existence of the feature will result in proper charting. On the other hand, properly collected and annotated sounding reports of the area may enable DMAHTC to accumulate sufficient evidence to justify the removal of the sounding from the chart.

3016. Preparation Of Sounding Reports

The procedures for preparing sounding reports have been designed to minimize the efforts of the shipboard observers, yet provide the essential information needed by DMAHTC. Blank OCEANIC SOUNDING REPORT forms are available from DMAHTC as a stock item or through DMA Representatives in Los Angeles/Long Beach, New Orleans, and Washington, D.C. Submission of plotted sounding tracks is not required. Annotated echograms and navigation logs are preferred. The procedure for collecting sounding reports is for the ship to operate a recording echo sounder while transiting an area where soundings are desired. Fixes and course changes are recorded in the log, and the event marker is used to note these events on the echogram. Both the log and echogram can then be sent to DMAHTC whenever convenient.

The following annotations or information should be clearly written on the echogram to ensure maximum use of the recorded depths:

1. **Ship's name**—At the beginning and end of each roll of echogram or portion.
2. **Date**—Annotated at 1200 hours each day and when starting and stopping the echo sounder, or at least once per roll.
3. **Time**—The echogram should be annotated at the beginning of the sounding run, at least once each hour thereafter, at every scale change, and at all breaks in the echogram record. Accuracy of these time marks is critical for correlation with ship's position.
4. **Time Zone**—Greenwich Mean Time (GMT) should be used if practicable. In the event local zone times are used, annotate echogram whenever clocks are reset and identify zone time in use. It is most important that the echogram and navigation log use the same time basis.

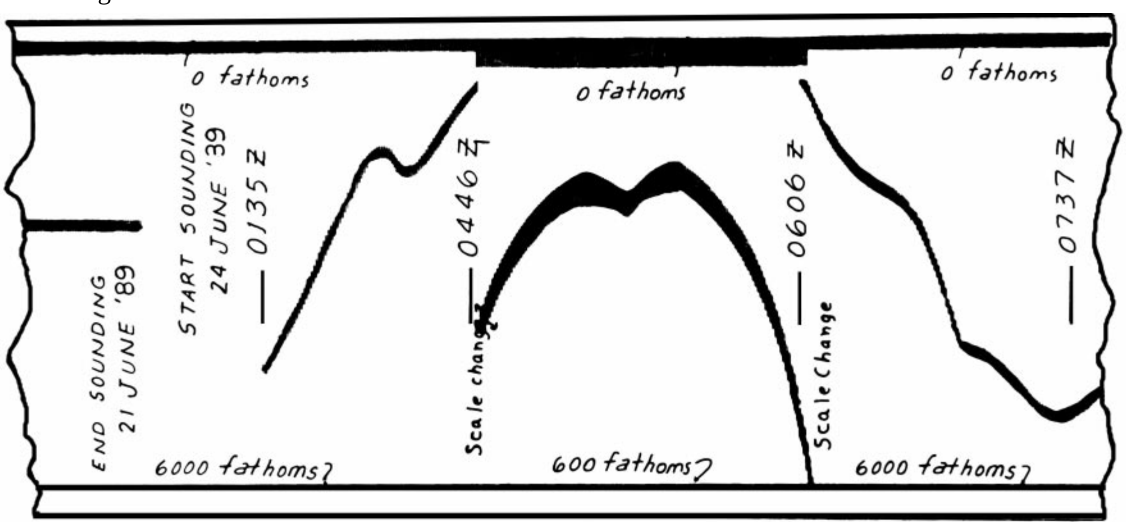


Figure 3016a. Properly annotated echo sounding record.

NAVIGATION LOG							REMARKS
DATE	TIME (GMT)	LAT.	LONG.	NAV. FIX	COURSE	SPEED	
11/2/83	0221	29°41'N	124°10'E	LORAN	093°	12.3	
	0340				097°	12.3	CHANGE COURSE
	0400	29°40'N	124°35'E	NOON FIX	097°	12.3	
	0728	29°35'N	125°22'E	LORAN	097°	12.3	
	0810				VARIOUS	8.2	REDUCE SPEED – MANUVERING TO AVOID FISHING BOATS
	0826	29°34'N	125°35.5'E	LORAN	097°	12.3	RESUME COURSE AND SPEED
	1011	29°32'N	125°56'E	EVENING STARS	097°	12.3	
	1620	29°23'N	127°22'E	LORAN	102°	12.4	CHANGE COURSE
	2230	29°06.2'N	128°48.5'E	RADAR STAR	102°	12.5	
	2305				102°	10.1	REDUCE SPEED

Figure 3016b. Typical navigation log for hydrographic reporting.

5. **Phase or scale changes**—If echosounder does not indicate scale setting on echogram automatically, clearly label all depth phase (or depth scale) changes and the exact time they occur. Annotate the upper and lower limits of the echogram if necessary.

Figure 3016a and Figure 3016b illustrates the data necessary to reconstruct a sounding track. If ship operations dictate that only periodic single ping soundings can be obtained, the depths may be recorded in the Remarks column. A properly annotated echogram is always strongly preferred by DMAHTC over single ping soundings whenever operations permit. The navigation log is vital to the reconstruction of a sounding track. Without the position information from the log, the echogram is virtually useless.

The data received from these reports is digitized and becomes part of the digital bathymetric data library of DMAHTC. This library is used as the basis of new chart compilation. Even in areas where numerous soundings already exist, sounding reports allow valuable cross-checking to verify existing data and more accurately portray the sea floor. This is helpful to our Naval forces and particularly to the submarine fleet, but is also useful to geologists, geophysicists, and other scientific disciplines.

A report of oceanic soundings should contain the following:

1. A completed Oceanic Sounding Report, Form DMAHTC 8053/1.
2. A detailed Navigation Log.
3. The echo sounding trace, properly annotated.

Each page of the report should be clearly marked with the ship's name and date, so that it can be identified if it becomes separated. Mail the report to:

Director
DMA Hydrographic/Topographic Center
MC, D-40
4600 Sangamore Rd.
Bethesda, MD, 20816-5003

OTHER HYDROGRAPHIC REPORTS

3017. Marine Information Reports

Marine Information Reports are reports of items of navigational interest such as the following:

1. Discrepancies in published information.
2. Changes in aids to navigation.
3. Electronic navigation reports.
4. Satellite navigation reports.
5. Radar navigation reports.
6. Magnetic disturbances.

Report any marine information which you believe may be useful to charting authorities or other mariners. Depending on the type of report, certain items of information are absolutely critical for a correct evaluation. The following general suggestions are offered to assist in reporting information that will be of maximum value:

1. The geographical position included in the report may be used to correct charts. Accordingly, it should be fixed by the most exact method available, more than one if possible.
2. If geographical coordinates are used to report position, they should be as exact as circumstances permit. Reference should be made to the chart by number, edition number, and date.
3. The report should state the method used to fix the position and an estimate of fix accuracy.
4. When reporting a position within sight of charted objects, the position may be expressed as bearings and ranges from them. Bearings should preferably be reported as true and expressed in degrees.
5. Always report the limiting bearings from the ship toward the light when describing the sectors in which a light is either visible or obscured. Although this is just the reverse of the form used to locate objects, it is the standard method used on DMAHTC nautical charts and in Light Lists.
6. A report prepared by one person should, if possible, be checked by another.

In most cases marine information can be adequately reported on one of the various forms printed by DMAHTC or NOS. It may be more convenient to annotate information directly on the affected chart and mail it to DMAHTC. As an example, it may be useful to sketch uncharted or erroneously charted shoals, buildings, or geological features directly on the chart. Appropriate supporting information should also be provided.

DMAHTC forwards reports applicable to NOS, NAVOCEANO, or Coast Guard products to the appropriate agency.

Reports by letter are just as acceptable as those prepared on regular forms. A letter report will often allow more flexibility in reporting details, conclusions, or recommendations concerning the observation. When reporting on the regular forms, if necessary use additional sheets to complete the details of an observation.

Reports are required concerning any errors in information

published on nautical charts or in nautical publications. The ports should be as accurate and complete as possible. This will result in corrections to the information including the issuance of Notice to Mariners changes when appropriate.

Report all changes, defects, establishment or discontinuance of navigational aids and the source of the information. Check your report against the light list, list of lights, Radio Aids to Navigation, and the largest scale chart of the area. If it is discovered that a new light has been established, report the light and its characteristics in a format similar to that carried in light lists and lists of lights. Forchanges and defects, report only elements that differ with light lists. If it is a lighted aid, identify by number. Defective aids to navigation in U.S. territorial waters should be reported immediately to the Commander of the local Coast Guard District.

3018. Electronic Navigation Reports

Electronic navigation systems such as GPS and LORAN have become an integral part of modern navigation. Reports on propagation anomalies or any unusual reception while using the electronic navigation system are desired.

Information should include:

1. Type of electronic navigation system and channel or frequency used.
2. Type of antenna: whip, vertical or horizontal wire.
3. Transmitting stations, rate or pair used.
4. Nature and description of the reception.
5. Type of signal match.
6. Date and time.
7. Position of own ship.
8. Manufacturer and model of receiver.

Calibration information is being collected in an effort to evaluate and improve the accuracy of the DMAHTC derived Loran signal propagation corrections incorporated in National Ocean Service Coastal Loran C charts. Loran C monitor data consisting of receiver readings with corresponding well defined reference positions are required. Mariners aboard vessels equipped with Loran C receiving units and having precise positioning capability independent of the Loran C system (i.e., docked locations or visual bearings, radar, GPS, Raydist, etc.) are requested to provide information to DMAHTC.

3019. Radar Navigation Reports

Reports of any unusual reception or anomalous propagation by radar systems caused by atmospheric conditions are especially desirable. Comments concerning the use of radar in piloting, with the locations and description of good radar targets, are particularly needed. Reports should include:

1. Type of radar, frequency, antenna height and type.
2. Manufacturer and model of the radar.
3. Date, time and duration of observed anomaly.
4. Position.
5. Weather and sea conditions.

Radar reception problems caused by atmospheric parameters are contained in four groups. In addition to the previously listed data, reports should include the following specific data for each group:

1. Unexplained echoes—Description of echo, apparent velocity and direction relative to the observer, and range.
2. Unusual clutter—Extent and Sector.
3. Extended detection ranges—Surface or airborne target, whether point or distributed target, such as a coastline or landmass.
4. Reduced detection ranges—Surface or airborne target, whether point or distributed target, such as a coastline or landmass.

3020. Magnetic Disturbances

Magnetic anomalies, the result of a variety of causes, exist in many parts of the world. DMAHTC maintains a record of such magnetic disturbances and whenever possible attempts to find an explanation. A better understanding of this phenomenon can result in more detailed charts which will be of greater value to the mariner.

The report of a magnetic disturbance should be as specific as possible, for instance: “Compass quickly swung 190° to 170°, remained offset for approximately 3 minutes and slowly returned.” Include position, ship’s course, speed, date, and time.

Whenever the readings of the standard magnetic compass are unusual, an azimuth check should be made as soon as possible and this information forwarded to DMAHTC.

PORT INFORMATION REPORTS

3021. Importance Of Port Information Reports

Port Information Reports provide essential information obtained during port visits which can be used to update and improve coastal, approach, and harbor charts as well as nautical publications including Sailing Directions, Coast Pilots, and Fleet Guides. Engineering drawings, hydrographic surveys and port plans showing new construction

affecting charts and publications are especially valuable.

Items involving navigation safety should be reported by message. Items which are not of immediate urgency, as well as additional supporting information may be submitted by the Port Information Report (DMAHTC Form 8330-1), or the Notice to Mariners Marine Information Report and Suggestion Sheet found in the back of each Notice to Mariners. Reports by letter are completely acceptable and may permit more reporting flexibility.

In some cases it may be more convenient and more effective to annotate information directly on a chart and mail it to DMAHTC. As an example, new construction, such as new port facilities, pier or breakwater modifications, etc., may be drawn on a chart in cases where a written report would be inadequate.

Specific Navy reporting requirements exist for ships visiting foreign ports. These reports are primarily intended to provide information for use in updating the Navy Port Directories. A copy of the navigation information resulting from port visits should be provided directly to DMAHTC by including DMAHTC WASHINGTON DC/MCC// as an INFO addressee on messages containing hydrographic information.

3022. What To Report

Coastal features and landmarks are almost constantly changing. What may at one time have been a major landmark may now be obscured by new construction, destroyed, or changed by the elements. Sailing Directions (Enroute) and Coast Pilots utilize a large number of photographs and line sketches. Photographs, particularly a series of overlapping views showing the coastline, landmarks, and harbor entrances are very useful. Photographs and negatives can be used directly as views or in the making of line sketches.

The following questions are suggested as a guide in preparing reports on coastal areas that are not included or that differ from the Sailing Directions and Coast Pilots.

Approach

1. What is the first landfall sighted?
2. Describe the value of soundings, radio bearings, GPS, LORAN, radar and other positioning systems in making a landfall and approaching the coast. Are depths, curves, and coastal dangers accurately charted?
3. Are prominent points, headlands, landmarks, and aids to navigation adequately described in Sailing Directions and Coast Pilots? Are they accurately charted?
4. Do land hazes, fog or local showers often obscure the prominent features of the coast?
5. Do discolored water and debris extend offshore? How far? Were tidal currents or rips experienced along the coasts or in approaches to rivers or bays?
6. Are any features of special value as radar targets?

Tides and Currents

1. Are the published tide and current tables accurate?
2. Does the tide have any special effect such as river bore? Is there a local phenomenon, such as double high or low water interrupted rise and fall?
3. Was any special information on tides obtained from local sources?
4. What is the set and drift of tidal currents along coasts, around headlands among islands, in coastal indentations?
5. Are tidal currents reversing or rotary? If rotary, do they rotate in a clockwise or counterclockwise direction?
6. Do subsurface currents affect the maneuvering of surface craft? If so, describe.
7. Are there any countercurrents, eddies, overfalls, or tide rips in the area? If so, locate.

River and Harbor Entrances

1. What is the depth of water over the bar, and is it subject to change? Was a particular stage of tide necessary to permit crossing the bar?
2. What is the least depth in the channel leading from sea to berth?
3. If the channel is dredged, when and to what depth and width? Is the channel subject to silting?
4. What is the maximum draft, length, and width of a vessel that can be taken into port?
5. If soundings were taken, what was the stage of tide? Were the soundings taken by echo sounder or lead line? If the depth information was received from other sources, what were they?
6. What was the date and time of water depth observations?

Hills, Mountains, and Peaks

1. Are hills and mountains conical, flat-topped, or of any particular shape?
2. At what range are they visible in clear weather?
3. Are they snowcapped throughout the year?
4. Are they cloud-covered at any particular time?
5. Are the summits and peaks adequately charted? Can accurate distances and/or bearings be obtained by sextant, pelorus, or radar?
6. What is the quality of the radar return?

Pilotage

1. Where is the signal station located?
2. Where does the pilot board the vessel? Are special arrangements necessary before a pilot boards?
3. Is pilotage compulsory? Is it advisable?
4. Will a pilot direct a ship in at night, during foul weather, or during periods of low visibility?

5. Where does the pilot boat usually lie?
6. Does the pilot boat change station during foul weather?
7. Describe the radiotelephone communication facilities available at the pilot station or pilot boat. What is the call-sign, frequency, and the language spoken?

General

1. What cautionary advice, additional data, and information on outstanding features should be given to a mariner entering the area for the first time?
2. At any time did a question or need for clarification arise while using DMAHTC, NOS, or Coast Guard products?
3. Were charted land contours useful while navigating using radar? Indicate the charts and their edition numbers.
4. Would it be useful to have radar targets or topographic features that aid in identification or position plotting described or portrayed in the Sailing Directions and Coast Pilots?

Photographs

The overlapping photograph method for panoramic views should be used. On the back of the photograph (negatives should accompany the required information), indicate the camera position by bearing and distance from a fixed, charted object if possible, name of the vessel, the date, time of exposure, and height of tide. All features of navigational value should be clearly and accurately identified on an overlay, if time permits. Bearings and distances (from the vessel) of uncharted features, identified on the print, should be included.

Radarscope Photography

Because of the value of radar as an aid to navigation, DMAHTC desires radarscope photographs. Guidelines for radar settings for radarscope photography are given in *Radar Navigation Manual, Pub. 1310*. Such photographs, reproduced in the Sailing Directions and Fleet Guides, supplement textual information concerning critical navigational areas and assist the navigator in correlating the radarscope presentation with the chart. To be of the greatest value, radarscope photographs should be taken at landfalls, sea buoys, harbor approaches, major turns in channels, constructed areas and other places where they will most aid the navigator. Two glossy prints of each photograph are needed. One should be unmarked, the other annotated.

Examples of desired photographs are images of fixed and floating navigational aids of various sizes and shapes as observed under different sea and weather conditions, and images of sea return and precipitation of various intensities. There should be two photographs of this type of image, one without the use of special anti clutter circuits and another showing remedial effects of these. Photographs of actual icebergs, growlers, and bergy bits under different sea conditions, correlated with photographs of their radarscope images are also desired.

Radarscope photographs should include the following annotations:

1. Wavelength.
2. Antenna height and rotation rate.
3. Range-scale setting and true bearing.
4. Antenna type (parabolic, slotted waveguide).
5. Weather and sea conditions, including tide.
6. Manufacturer’s model identification.
7. Position at time of observation.
8. Identification of target by Light List, List of Lights, or chart.
9. Camera and exposure data.

Other desired annotations include:

1. Beam width between half-power points.
2. Pulse repetition rate.
3. Pulse duration (width).
4. Antenna aperture (width).
5. Peak power.
6. Polarization.
7. Settings of radar operating controls, particularly use of special circuits.
8. Characteristics of display (stabilized or unstabilized), diameter, etc.

Port Regulations and Restrictions

Sailing Directions (Planning Guides) are concerned with pratique, pilotage, signals, pertinent regulations, warning areas, and navigational aids. Updated and new information is constantly needed by DMAHTC. Port information is best reported on the prepared “Port Information Report”, DMAHTC form 8330-1. If this form is not available, the following questions are suggested as a guide to the requested data.

1. Is this a port of entry for overseas vessels?
2. If not a port of entry where must vessel go for customs entry and pratique?
3. Where do customs, immigration, and health officials board?
4. What are the normal working hours of officials?
5. Will the officials board vessels after working hours? Are there overtime charges for after-hour services?
6. If the officials board a vessel underway, do they remain on board until the vessel is berthed?
7. Were there delays? If so, give details.
8. Were there any restrictions placed on the vessel?

9. Was a copy of the Port Regulations received from the local officials?
10. What verbal instructions were received from the local officials?
11. What preparations prior to arrival would expedite formalities?
12. Are there any unwritten requirements peculiar to the port?
13. What are the speed regulations?
14. What are the dangerous cargo regulations?
15. What are the flammable cargo and fueling regulations?.
16. Are there special restrictions on blowing tubes, pumping bilges. oil pollution, fire warps, etc.?
17. Are the restricted and anchorage areas correctly shown on charts, and described in the Sailing Directions and Coast Pilots?
18. What is the reason for the restricted areas; gunnery, aircraft operating, waste disposal, etc.?
19. Are there specific hours of restrictions, or are local blanket notices issued?
20. Is it permissible to pass through, but not anchor in, restricted areas?
21. Do fishing boats, stakes, nets, etc., restrict navigation?
22. What are the heights of overhead cables, bridges, and pipelines?
23. What are the locations of submarine cables, their landing points, and markers?
24. Are there ferry crossings or other areas of heavy local traffic?
25. What is the maximum draft, length, and breadth of a vessel that can enter?

Port Installations

Much of the port information which appears in the Sailing Directions and Coast Pilots is derived from visit reports and port brochures submitted by mariners. Comments and recommendations on entering ports are needed so that corrections to these publications can be made.

If extra copies of local port plans, diagrams, regulations, brochures, photographs, etc., can be obtained, send them to DMAHTC. It is not essential that they be printed in English. Local pilots, customs officials, company agents, etc., are usually good information sources.

Much of the following information is included in the regular Port Information Report, but may be used as a check-off list when submitting a letter report.

General

1. Name of the port.
2. Date of observation and report.
3. Name and type of vessel.
4. Gross tonnage.
5. Length (overall).
6. Breadth (extreme).
7. Draft (fore and aft).
8. Name of captain and observer.
9. U.S. mailing address for acknowledgment.

Tugs and Locks

1. Are tugs available or obligatory? What is their power?
2. If there are locks, what is the maximum size and draft of a vessel that can be locked through?

Cargo Handling Facilities

1. What are the capacities of the largest stationary, mobile, and floating cranes available? How was this information obtained?
2. What are the capacities, types, and number of lighters and barges available?
3. Is special cargo handling equipment available (e.g.) grain elevators, coal and ore loaders, fruit or sugar conveyors, etc.?
4. If cargo is handled from anchorage, what methods are used? Where is the cargo loaded? Are storage facilities available there?

Supplies

1. Are fuel oils, diesel oils, and lubricating oils available? If so, in what quantity?

Berths

1. What are the dimensions of the pier, wharf, or basin used?
2. What are the depths alongside? How were they obtained?
3. Describe berth/berths for working containers or roll-on/ roll-off cargo.
4. Does the port have berth for working deep draft tankers? If so, describe.
5. What storage facilities are available, both dry and refrigerated?
6. Are any unusual methods used when docking? Are special precautions necessary at berth?

Medical, Consular, and Other Services

1. Is there a hospital or the services of a doctor and dentist available?
2. Is there a United States consulate? Where is it located? If none, where is the nearest?

Anchorages

1. What are the limits of the anchorage areas?
2. In what areas is anchorage prohibited?
3. What is the depth, character of the bottom, types of holding ground, and swinging room avaiable?
4. What are the effects of weather, sea, swell, tides, currents on the anchorages?
5. Where is the special quarantine anchorage?
6. Are there any unusual anchorage restrictions?

Repairs and Salvage

1. What are the capacities of drydocks and marine railways, if available?
2. What repair facilities arc available? Are there repair facilities for electrical and electronic equipment?
3. Are divers and diving gear available?
4. Are there salvage tugs available? What is the size and operating radius?
5. Are any special services, (e.g., compass compensation or degaussing,) available?

MISCELLANEOUS HYDROGRAPHIC REPORTS

3023. Ocean Current Reports

The set and drift of ocean currents are of great concern to the navigator. Only with the correct current information can the shortest and most efficient voyages be planned. As with all forces of nature, most currents vary considerably with time at a given location. Therefore, it is imperative that DMAHTC receive ocean current reports on a continuous basis.

The general surface currents along the principal trade routes of the world are well known; however, in other less traveled areas the current has not been well defined because of the lack of information. Detailed current reports from those areas are especially valuable.

An urgent need exists for more inshore current reports along all coasts of the world because data in these regions are scarce. Furthermore, information from deep draft ships is needed as this type of vessel is significantly influenced by the deeper layer of surface currents.

The CURRENT REPORT form, NAVOCEANO 3141/6, is designed to facilitate passing information to NAVOCEANO so that all mariners may benefit. The form is self-explanatory and can be used for ocean or coastal current information. Reports by the navigator will contribute significantly to accurate current information for nautical charts, Current Atlases, Pilot Charts, Sailing Directions and other special charts and publications.

3024. Route Reports

Route Reports enable DMAHTC, through its Sailing Directions (Planning Guides), to make recommendations for ocean passages based upon the actual experience of mariners. Of particular importance are reports of routes used by very large ships and from any ship in regions where, from experience and familiarity with local conditions, mariners have devised routes that differ from the "preferred track." In addition, because of the many and varied local conditions which must be taken into account, coastal route information is urgently needed for updating both Sailing Directions and Coast Pilots.

A Route Report should include a comprehensive summary of the voyage with reference to currents, dangers, weather, and the draft of the vessel. If possible, each report should answer the following questions and should include any other data that may be considered pertinent to the particular route. All information should be given in sufficient detail to assure accurate conclusions and appropriate recommendations. Some questions to be answered are:

1. Why was the route selected?
2. Were anticipated conditions met during the voyage?

CHAPTER 31

THE OCEANS

INTRODUCTION

3100. The Importance Of Oceanography

Oceanography is the application of the sciences to the phenomena of the oceans. It includes a study of their physical, chemical, and geological forms, and biological features. Thus, it embraces the widely separated fields of geography, geology, chemistry, physics, and biology, along with their many subdivisions, such as sedimentation, ecology, bacteriology, biochemistry, hydrodynamics, acoustics, and optics.

The oceans cover 70.8 percent of the surface of the earth. The Atlantic covers 16.2 percent, the Pacific 32.4 percent (3.2 percent more than the land area of the entire earth), the Indian Ocean 14.4 percent, and marginal and adjacent areas (of which the largest is the Arctic Ocean) 7.8 percent. Their extent alone makes them an important subject for study. However, greater incentive lies in their use for transportation, their influence upon weather and climate, and their potential as a source of power, food, fresh water, minerals, and organic substances.

3101. Origin Of The Oceans

The structure of the continents is fundamentally different from that of the oceans. The rocks underlying the ocean floors are more dense than those underlying the continents. According to one theory, all the earth's crust floats on a central liquid core, and the portions that make up the continents, being lighter, float with a higher freeboard. Thus, the thinner areas, composed of heavier rock, form natural basins where water has collected.

The shape of the oceans is constantly changing due to continental drift. The surface of the earth consists of many different "**plates**." These plates are joined along **fracture** or **fault lines**. There is constant and measurable movement of these plates at rates of 0.02 meters per year or more.

The origin of the water in the oceans is unclear. Although some geologists have postulated that all the water existed as vapor in the atmosphere of the primeval earth, and that it fell in great torrents of rain as soon as the earth cooled sufficiently, another school holds that the atmosphere of the original hot earth was lost, and that the water gradually accumulated as it was given off in steam by volcanoes, or worked to the surface in hot springs.

Most of the water on the earth's crust is now in the oceans–about 1,370,000,000 cubic kilometers, or about 85 percent of the total. The mean depth of the ocean is 3,795 meters, and the total area is 360,000,000 square kilometers.

CHEMISTRY OF THE OCEANS

3102. Chemical Description

Oceanographic chemistry may be divided into three main parts: the chemistry of (1) seawater, (2) marine sediments, and (3) organisms living in the sea. The first is of particular interest to the navigator.

Chemical properties of seawater are usually determined by analyzing samples of water obtained at various locations and depths. Samples of water from below the surface are obtained with special bottles designed for this purpose. The open bottles are mounted in a rosette which is attached to the end of a wire cable which contains insulated electrical wires. The rosette is lowered to the depth of the deepest sample, and a bottle is closed electronically. As the rosette is raised to the surface, other bottles are closed at the desired depths. Sensors have also been developed to measure a few chemical properties of sea water continuously.

Physical properties of seawater are dependent primarily upon salinity, temperature, and pressure. However, factors like motion of the water, and the amount of suspended matter, affect such properties as color and transparency, conduction of heat, absorption of radiation, etc.

3103. Salinity

Salinity is a measure of the amount of dissolved solid material in the water. It has been defined as the total amount of solid material in grams contained in one kilogram of seawater when carbonate has been converted to oxide, bromine and iodine replaced by chlorine, and all organic material completely oxidized. It is usually expressed as parts per thousand (by weight), for example the average salinity of sea water is 35 grams per kilogram which would be written "35 ppt" or "35 ‰". Historically the determination of salinity was a slow and difficult process, while the amount of chlorine ions (plus the chlorine equivalent of the bromine

and iodine), called **chlorinity**, could be determined easily and accurately by titration with silver nitrate. From chlorinity, the salinity was determined by a relation based upon the measured ratio of chlorinity to total dissolved substances:

$$\text{Salinity} = 1.80655 \times \text{Chlorinity}$$

This is now called the absolute salinity, (S_A). With titration techniques, salinity could be determined to about 0.02 parts per thousand.

This definition of salinity has now been replaced by the **Practical Salinity Scale**, (S). Using this scale, the salinity of a seawater sample is defined as the ratio between the conducutivity of the sample and the conductivity of a standard potassium chloride (KCl) sample.

As salinity on the practical scale is defined to be conservative with respect to addition and removal of water, the entire salinity range is accessible through precise weight dilution or evaporation without additional definitions. Since practical salinity is a ratio, it has no physical units but is designated **practical salinity units**, or **psu**. The Practical Salinity Scale, combined with modern conductivity cells and bench salinometers, provides salinity measurements which are almost an order of magnitude more accurate and precise, about 0.003 psu, than titration. Numerically, absolute salinity and salinity are nearly equal.

It has also been found that electrical conductivity is better related to density than chlorinity. Since one of the main reasons to measure salinity is to deduce the density, this favors the Practical Salinity Scale as well.

Salinity generally varies between about 33 and 37 psu. However, when the water has been diluted, as near the mouth of a river or after a heavy rainfall, the salinity is somewhat less; and in areas of excessive evaporation, the salinity may be as high as 40 psu. In certain confined bodies of water, notably the Great Salt Lake in Utah, and the Dead Sea in Asia Minor, the salinity is several times this maximum.

3104. Temperature

Temperature in the ocean varies widely, both horizontally and with depth. Maximum values of about 32°C are encountered at the surface in the Persian Gulf in summer, and the lowest possible values of about –2°C; the usual minimum freezing point of seawater) occur in polar regions.

Except in the polar regions, the vertical distribution of temperature in the sea nearly everywhere shows a decrease of temperature with depth. Since colder water is denser (assuming the same salinity), it sinks below warmer water. This results in a temperature distribution just opposite to that of the earth's crust, where temperature increases with depth below the surface of the ground.

In the sea there is usually a mixed layer of isothermal water below the surface, where the temperature is the same as that of the surface. This layer is caused by two physical processes: wind mixing, and convective overturning as surface water cools and becomes more dense. The layer is best developed in the Arctic and Antarctic regions, and in seas like the Baltic and Sea of Japan during the winter, where it may extend to the bottom of the ocean. In the Tropics, the wind-mixed layer may exist to a depth of 125 meters, and may exist throughout the year. Below this layer is a zone of rapid temperature decrease, called the **thermocline**. At a depth greater than 400 m, the temperature everywhere is below 15°C. In the deeper layers, fed by cooled waters that have sunk from the surface in the Arctic and Antarctic, temperatures as low as –2°C exist.

In the colder regions the cooling creates the convective overturning and isothermal water in the winter; but in the summer a seasonal thermocline is created as the upper water becomes warmer. A typical curve of temperature at various depths is shown in Figure 3110a. Temperature is commonly measured with either a platinum or copper resistance thermometer or a thermistor (devices that measure the change in conductivity of a semiconductor with change in temperature). The **CTD (conductivity-temperature-depth)** is an instrument that generates continuous signals as it is lowered into the ocean; temperature is determined by means of a platinum resistance thermometer, salinity by conductivity, and depth by pressure. These signals are transmitted to the surface through a cable and recorded. Accuracy of temperature measurement is 0.005°C and resolution an order of magnitude better.

A method commonly used to measure upper ocean temperature profiles from a vessel which is underway is the **expendable bathythermograph (XBT)**. The XBT uses a thermistor and is connected to the vessel by a fine wire. The wire is coiled inside the probe, and as the probe freefalls in the ocean, the wire pays out. Depth is determined by elapsed time and a known sink rate. Depth range is determined by the amount of wire stored in the probe; the most common model has a depth range of 450 meters. At the end of the drop, the wire breaks and the probe falls to the ocean bottom. One instrument of this type is dropped from an aircraft; the data is relayed to the aircraft from a buoy to which the wire of the XBT is attached. The accuracy and precision of an XBT is about 0.1°C.

3105. Pressure

The appropriate international standard (SI) unit for pressure in oceanography is 1 $kPa = 10^3\ Pa$ where Pa is a Pascal and is equal to one Newton per square meter. A more commonly used unit is a bar, which is nearly equal to 1 atmosphere (atmospheric pressure is measured with a barometer and may be read as millibars). Water pressure is expressed in terms of decibars, 10 of these being equal to 1 bar. One decibar is equal to nearly $1\ ^1/_2$ pounds per square inch. This unit is convenient because it is very nearly the pressure exerted by 1 meter of water. Thus, the pressure in

decibars is approximately the same as the depth in meters, the unit of depth.

Although virtually all of the physical properties of seawater are affected to a measurable extent by pressure, the effect is not as great as those of salinity and temperature. Pressure is of particular importance to submarines, directly because of the stress it induces on the hull and structures, and indirectly because of its effect upon buoyancy.

3106. Density

Density is mass per unit of volume. The appropriate SI unit is kilograms per cubic meter. The density of seawater depends upon salinity, temperature, and pressure. At constant temperature and pressure, density varies with salinity. A temperature of 0°C and atmospheric pressure are considered standard for density determination. The effects of thermal expansion and compressibility are used to determine the density at other temperatures and pressures. Density changes at the surface generally do not affect the draft or trim of a ship. But density changes at a particular subsurface pressure affect the buoyancy of submarines because they are ballasted to be neutrally buoyant. For oceanographers, density is important because of its relationship to ocean currents.

Open ocean values of density range from about 1,021 kilograms per cubic meter at the surface to about 1,070 kilograms per cubic meter at 10,000 meters depth. As a matter of convenience, it is usual in oceanography to define a density anomaly which is equal to the density minus 1,000 kilograms per cubic meter. Thus, when an oceanographer speaks of seawater with a density of 25 kilograms per cubic meter, the actual density is 1,025 kilograms per cubic meter.

The greatest changes in density of seawater occur at the surface, where the water is subject to influences not present at depths. At the surface, density is decreased by precipitation, run-off from land, melting ice, or heating. When the surface water becomes less dense, it tends to float on top of the more dense water below. There is little tendency for the water to mix, and so the condition is one of stability. The density of surface water is increased by evaporation, formation of sea ice, and by cooling. If the surface water becomes more dense than that below, convection currents cause vertical mixing. The more dense surface water sinks and mixes with less dense water below. The resultant layer of water is of intermediate density. This process continues until the density of the mixed layer becomes less than that of the water below. The convective circulation established as part of this process can create very deep uniform mixed layers.

If the surface water becomes sufficiently dense, it sinks all the way to the bottom. If this occurs in an area where horizontal flow is unobstructed, the water which has descended spreads to other regions, creating a dense bottom layer. Since the greatest increase in density occurs in polar regions, where the air is cold and great quantities of ice form, the cold, dense polar water sinks to the bottom and then spreads to lower latitudes. In the Arctic Ocean region, the cold, dense water is confined by the Bering Strait and the underwater ridge from Greenland to Iceland to Europe. In the Antarctic, however, there are no similar geographic restrictions and large quantities of very cold, dense water formed there flow to the north along the ocean bottom. This process has continued for a sufficiently long period of time that the entire ocean floor is covered with this dense water, thus explaining the layer of cold water at great depths in all the oceans.

In some respects, oceanographic processes are similar to those occurring in the atmosphere. The convective circulation in the ocean is similar to that in the atmosphere. Masses of water of uniform characteristics are analogous to air masses.

3107. Compressibility

Seawater is nearly incompressible, its coefficient of compressibility being only 0.000046 per bar under standard conditions. This value changes slightly with changes in temperature or salinity. The effect of compression is to force the molecules of the substance closer together, causing it to become more dense. Even though the compressibility is low, its total effect is considerable because of the amount of water involved. If the compressibility of seawater were zero, sea level would be about 90 feet higher than it is now.

Compressibility is inversely proportional to temperature, i.e., cold water is more compressible than warm water. Waters which flow into the North Atlantic from the Mediterranean and Greenland Seas are equal in density, but because the water from the Greenland Sea is colder, it is more compressible and therefore becomes denser at depth. These waters from the Greenland Sea are therefore found beneath those waters which derive their properties from the Mediterranean.

3108. Viscosity

Viscosity is resistance to flow. Seawater is slightly more viscous than freshwater. Its viscosity increases with greater salinity, but the effect is not nearly as marked as that occurring with decreasing temperature. The rate is not uniform, becoming greater as the temperature decreases. Because of the effect of temperature upon viscosity, an incompressible object might sink at a faster rate in warm surface water than in colder water below. However, for most objects, this effect may be more than offset by the compressibility of the object.

The actual relationships existing in the ocean are considerably more complex than indicated by the simple explanation here, because of turbulent motion within the sea. The disturbing effect is called **eddy viscosity**.

3109. Specific Heat

Specific Heat is the amount of heat required to raise the temperature of a unit mass of a substance a stated amount. In oceanography, specific heat is stated, in SI units,

as the number of Joules needed to raise 1 kilogram of a given substance 1°C. Specific heat at constant pressure is usually the quantity desired when liquids are involved, but occasionally the specific heat at constant volume is required. The ratio of these two quantities is directly related to the speed of sound in seawater.

The specific heat of seawater decreases slightly as salinity increases. However, it is much greater than that of land. The ocean is a giant storage area for heat. It can absorb large quantities of heat with very little change in temperature. This is partly due to the high specific heat of water and partly due to mixing in the ocean that distributes the heat throughout a layer. Land has a lower specific heat and, in addition, all heat is lost or gained from a thin layer at the surface; there is no mixing. This accounts for the greater temperature range of land and the atmosphere above it, resulting in monsoons, and the familiar land and sea breezes of tropical and temperate regions.

3110. Sound Speed

The speed of sound in sea water is a function of its density, compressibility and, to a minor extent, the ratio of specific heat at constant pressure to that at constant volume. As these properties depend on the temperature, salinity and pressure (depth) of sea water, it is customary to relate the speed of sound directly to the water temperature, salinity and pressure. An increase in any of these three properties causes an increase in the sound speed; the converse is true also. Figure 3110a portrays typical mid-ocean profiles of temperature and salinity; the resultant sound speed profile is shown in Figure 3110b.

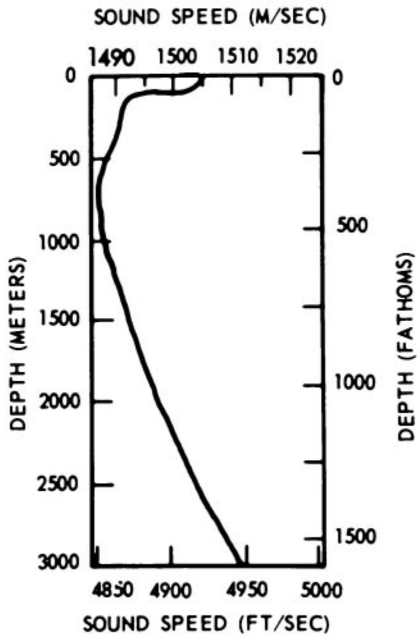


Figure 3110b. Resultant sound speed profile based on the temperature and salinity profile in Figure 3110a.

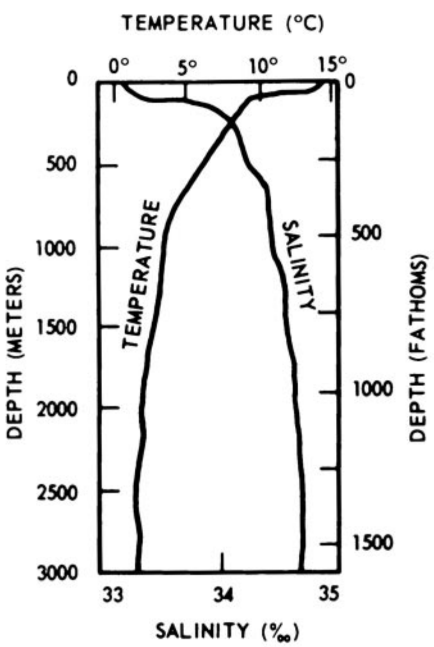


Figure 3110a. Typical variation of temperature and salinity with depth for a mid-latitude location.

The speed of sound changes by 3 to 5 meters per second per °C temperature change, by about 1.3 meters per second per psu salinity change and by about 1.7 meters per second per 100 m depth change. A simplified formula adapted from Wilson's (1960) equation for the computation of the sound speed in sea water is:

$$U = 1449 + 4.6T - 0.055T^2 + 0.0003T^3 + 1.39(S - 35) + 0.017D$$

where U is the speed (m/s), T is the temperature (°C), S is the salinity (psu), and D is depth (m).

3111. Thermal Expansion

One of the more interesting differences between salt and fresh water relates to thermal expansion. Saltwater continues to become more dense as it cools to the freezing point; freshwater reaches maximum density at 4°C and then expands (becomes less dense) as the water cools

to 0°C and freezes. This means that the convective mixing of freshwater stops at 4°C; freezing proceeds very rapidly beyond that point. The rate of expansion with increased temperature is greater in seawater than in fresh water. Thus, at temperature 15°C, and atmospheric pressure, the coefficient of thermal expansion is 0.000151 per degree Celsius for freshwater, and 0.000214 per degree Celsius for average seawater. The coefficient of thermal expansion increases not only with greater salinity, but also with increased temperature and pressure. At a salinity of 35 psu, the coefficient of surface water increases from 0.000051 per degree Celsius at 0°C to 0.000334 per degree Celsius at 31°C. At a constant temperature of 0°C and a salinity of 34.85 psu, the coefficient increases to 0.000276 per degree Celsius at a pressure of 10,000 decibars (a depth of approximately 10,000 meters).

3112. Thermal Conductivity

In water, as in other substances, one method of heat transfer is by conduction. Freshwater is a poor conductor of heat, having a coefficient of thermal conductivity of 582 Joules per second per meter per degree Celsius. For seawater it is slightly less, but increases with greater temperature or pressure.

However, if turbulence is present, which it nearly always is to some extent, the processes of heat transfer are altered. The effect of turbulence is to increase greatly the rate of heat transfer. The “eddy” coefficient used in place of the still-water coefficient is so many times larger, and so dependent upon the degree of turbulence, that the effects of temperature and pressure are not important.

3113. Electrical Conductivity

Water without impurities is a very poor conductor of electricity. However, when salt is in solution in water, the salt molecules are ionized and become carriers of electricity. (What is commonly called freshwater has many impurities and is a good conductor of electricity; only pure distilled water is a poor conductor.) Hence, the electrical conductivity of seawater is directly proportional to the number of salt molecules in the water. For any given salinity, the conductivity increases with an increase in temperature.

3114. Radioactivity

Although the amount of radioactive material in seawater is very small, this material is present in marine sediments to a greater extent than in the rocks of the earth’s crust. This is probably due to precipitation of radium or other radioactive material from the water. The radioactivity of the top layers of sediment is less than that of deeper layers. This may be due to absorption of radioactive material in the soft tissues of marine organisms.

3115. Transparency

The two basic processes that alter the underwater distribution of light are absorption and scattering. Absorption is a change of light energy into other forms of energy; scattering entails a change in direction of the light, but without loss of energy. If seawater were purely absorbing, the loss of light with distance would be given by $I_x = I_0 e^{-ax}$ where I_x is the intensity of light at distance x, I_0 is the intensity of light at the source, and “a” is the absorption coefficient in the same units with which distance is measured. In a pure scattering medium, the transmission of light is governed by the same power law only in this case the exponential term is $I_0 e^{-bx}$, where “b” is the volume scattering coefficient. The attenuation of light in the ocean is defined as the sum of absorption and scattering so that the attenuation coefficient, c, is given by c = a + b. In the ocean, the attenuation of light with depth depends not only on the wavelength of the light but also the clarity of the water. The clarity is mostly controlled by biological activity although at the coast, sediments transported by rivers or resuspended by wave action can strongly attenuate light.

Attenuation in the sea is measured with a **transmissometer**. Transmissometers measure the attenuation of light over a fixed distance using a monochromatic light source which is close to red in color. Transmissometers are designed for in situ use and are usually attached to a CTD.

Since sunlight is critical for almost all forms of plant life in the ocean, oceanographers developed a simple method to measure the penetration of sunlight in the sea using a white disk 31 centimeters (a little less than 1 foot) in diameter which is called a **Secchi disk**. This is lowered into the sea, and the depth at which it disappears is recorded. In coastal waters the depth varies from about 5 to 25 meters. Offshore, the depth is usually about 45 to 60 meters. The greatest recorded depth at which the disk has disappeared is 79 meters in the eastern Weddell Sea. These depths, D, are sometimes reported as a diffuse attenuation (or “extinction”) coefficient, k, where k = 1.7/D and the penetration of sunlight is given by $I_z = I_0 e^{-kz}$ where z is depth and I_0 is the energy of the sunlight at the ocean’s surface.

3116. Color

The color of seawater varies considerably. Water of the Gulf Stream is a deep indigo blue, while a similar current off Japan was named Kuroshio (Black Stream) because of the dark color of its water. Along many coasts the water is green. In certain localities a brown or brownish-red water has been observed. Colors other than blue are caused by biological sources, such as plankton, or by suspended sediments from river runoff.

Offshore, some shade of blue is common, particularly in tropical or subtropical regions. It is due to scattering of sunlight by minute particles suspended in the water, or by molecules of the water itself. Because of its short wavelength, blue light is more effectively scattered than light of

longer waves. Thus, the ocean appears blue for the same reason that the sky does. The green color often seen near the coast is a mixture of the blue due to scattering of light and a stable soluble yellow pigment associated with phytoplankton. Brown or brownish-red water receives its color from large quantities of certain types of **algae**, microscopic plants in the sea, or from river runoff.

3117. Bottom Relief

Compared to land, relatively little is known of relief below the surface of the sea. The development of an effective echo sounder in 1922 greatly simplified the determination of bottom depth. Later, a recording echo sounder was developed to permit the continuous tracing of a bottom profile. The latest sounding systems employ an array of echosounders aboard a single vessel, which continuously sound a wide swath of ocean floor. This has contributed immensely to our knowledge of bottom relief. By this means, many undersea mountain ranges, volcanoes, rift valleys, and other features have been discovered.

Along most of the coasts of the continents, the bottom slopes gradually downward to a depth of about 130 meters or somewhat less, where it falls away more rapidly to greater depths. This **continental shelf** averages about 65 kilometers in width, but varies from nothing to about 1400 kilometers, the widest part being off the Siberian Arctic coast. A similar shelf extending outward from an island or group of islands is called an **island shelf**. At the outer edge of the shelf, the steeper slope of 2° to 4° is called the **continental slope**, or the **island slope**, according to whether it surrounds a continent or a group of islands. The shelf itself is not uniform, but has numerous hills, ridges, terraces, and canyons, the largest being comparable in size to the Grand Canyon.

The relief of the ocean floor is comparable to that of land. Both have steep, rugged mountains, deep canyons, rolling hills, plains, etc. Most of the ocean floor is considered to be made up of a number of more-or-less circular or oval depressions called **basins**, surrounded by walls (**sills**) of lesser depth.

A wide variety of submarine features has been identified and defined. Some of these are shown in Figure 3117. Detailed definitions and descriptions of such features can be found in Kennett (1982) or Fairbridge (1966). The term **deep** may be used for a very deep part of the ocean, generally that part deeper than 6,000 meters.

The average depth of water in the oceans is 3795 meters (2,075 fathoms), as compared to an average height of land above the sea of about 840 meters. The greatest known depth is 11,524 meters, in the Marianas Trench in the Pacific. The highest known land is Mount Everest, 8,840 meters. About 23 percent of the ocean is shallower than 3,000 meters, about 76 percent is between 3,000 and 6,000 meters, and a little more than 1 percent is deeper than 6,000 meters.

3118. Marine Sediments

The ocean floor is composed of material deposited through the ages. This material consists principally of (1) earth and rocks washed into the sea by streams and waves, (2) volcanic ashes and lava, and (3) the remains of marine organisms. Lesser amounts of land material are carried into the sea by glaciers, blown out to sea by wind, or deposited by chemical means. This latter process is responsible for the **manganese nodules** that cover some parts of the ocean floor. In the ocean, the material is transported by ocean currents, waves, and ice. Near shore the material is deposited at the rate of about 8 centimeters in 1,000 years, while in the deep water offshore the rate is only about 1 centimeter in 1,000 years. Marine deposits in water deep enough to be relatively free from wave action are subject to little erosion. Recent studies have shown that some bottom currents are strong enough to move sediments. There are turbidity currents, similar to land slides, that move large masses of sediments. **Turbidity currents** have been known to rip apart large transoceanic cables on the ocean bottom. Because of this and the slow rate of deposit, marine sediments provide a better geological record than does the land.

Marine sediments are composed of individual particles of all sizes from the finest clay to large boulders. In general, the inorganic deposits near shore are relatively coarse (sand, gravel, shingle, etc.), while those in deep water are much finer (clay). In some areas the siliceous remains of marine organisms or calcareous deposits of either organic or inorganic origin predominate on the ocean floor.

A wide range of colors is found in marine sediments. The lighter colors (white or a pale tint) are usually associated with coarse-grained quartz or limestone deposits. Darker colors (red, blue, green, etc.) are usually found in mud having a predominance of some mineral substance, such as an oxide of iron or manganese. Black mud is often found in an area that is little disturbed, such as at the bottom of an inlet or in a depression without free access to other areas.

Marine sediments are studied primarily through bottom samples. Samples of surface deposits are obtained by means of a “snapper” (for mud, sand, etc.) or “dredge” (usually for rocky material). If a sample of material below the bottom surface is desired, a “coring” device is used. This device consists essentially of a tube driven into the bottom by weights or explosives. A sample obtained in this way preserves the natural order of the various layers. Samples of more than 100 feet in depth have been obtained using coring devices.

3119. Satellite Oceanography

Weather satellites are able to observe ocean surface temperatures in cloud free regions by using infrared sensors. Although these sensors are only able to penetrate a few millimeters into the ocean, the temperatures that they yield are

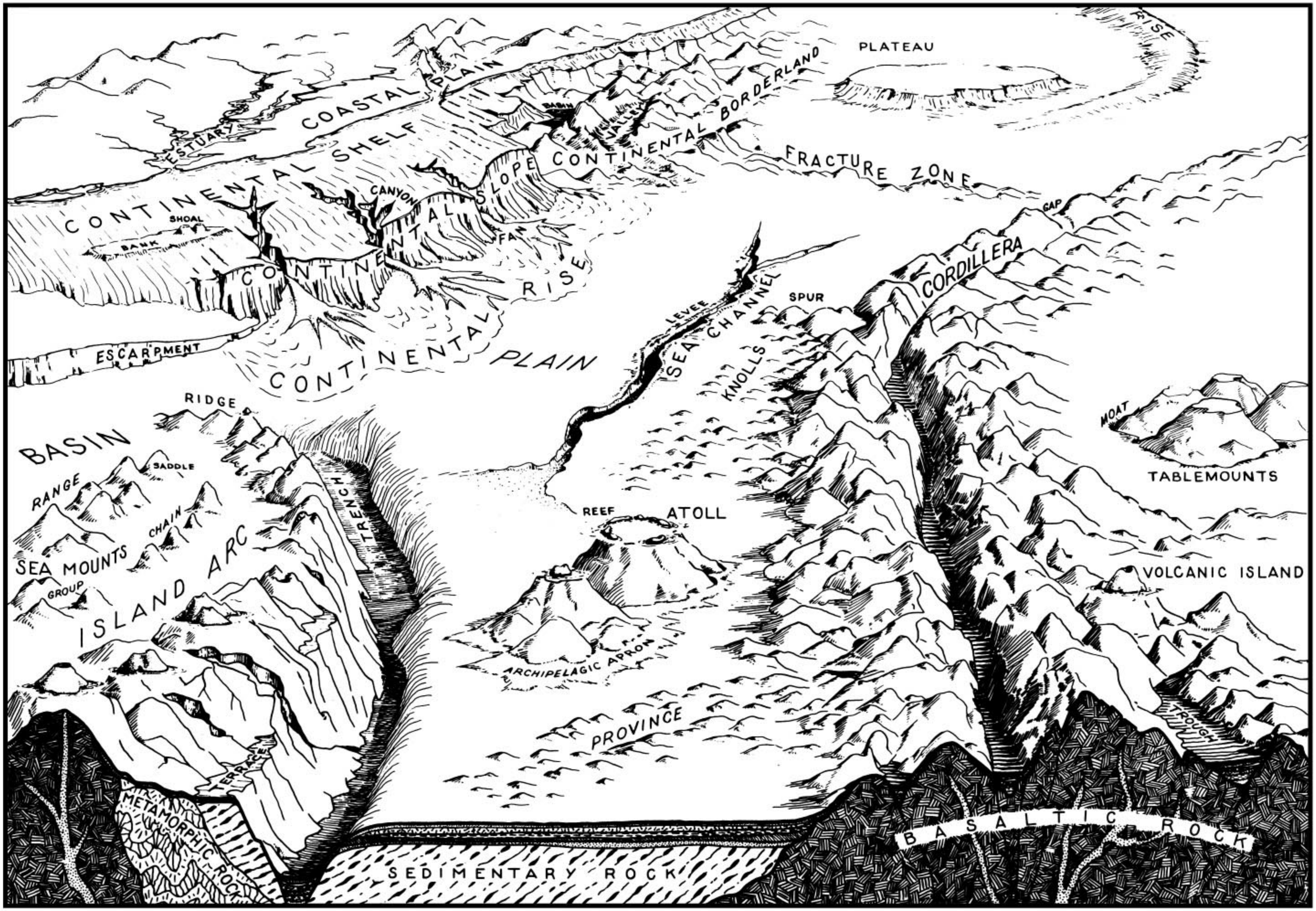


Figure 3117. Ocean basin features.

representative of upper ocean conditions except when the air is absolutely calm during daylight hours. For cloud covered regions, it is usually possible to wait a few days for the passage of a cold front and then use a sequence of infrared images to map the ocean temperature over a region. The patterns of warm and cold water yield information on ocean currents, the existence of fronts and eddies, and the temporal and spatial scales of ocean processes.

Other satellite sensors are capable of measuring ocean color, ice coverage, ice age, ice edge, surface winds and seas, ocean currents, and the shape of the surface of the ocean. (The latter is controlled by gravity and ocean circulation patterns. See Chapter 2.) The perspective provided by these satellites is a global one and in some cases they yield sufficient quantities of data that synoptic charts of the ocean surface, similar to weather maps and pilot charts, can be provided to the mariner for use in navigation.

The accuracy of satellite observations of the ocean surface depends, in many cases, on calibration procedures which use observations of sea surface conditions provided by mariners. These observations include marine weather observations, expendable bathythermograph soundings, and currents measured by electromagnetic logs or acoustic Doppler current profilers. Care and diligence in these observations will improve the accuracy and the quality of satellite data.

3120. Synoptic Oceanography

Oceanographic data provided by ships, buoys, and satellites are analyzed by the Naval Oceanographic Office and the National Meteorological Center. These data are utilized in computer models both to provide a synoptic view of ocean conditions and to predict how these conditions will change in the future. These products are available to the mariner via radio or satellite.

CHAPTER 32

OCEAN CURRENTS

TYPES AND CAUSES OF CURRENTS

3200. Definitions

The movement of ocean water is one of the two principal sources of discrepancy between dead reckoned and actual positions of vessels. Water in motion is called a current; the direction toward which it moves is called set, and its speed is called drift. Modern shipping speeds have lessened the impact of currents on a typical voyage, and since electronic navigation allows continuous adjustment of course, there is less need to estimate current set and drift before setting the course to be steered. Nevertheless, a knowledge of ocean currents can be used in cruise planning to reduce transit times. Ocean current models are an integral part of ship routing systems.

Oceanographers have developed a number of methods of classifying currents in order to facilitate descriptions of their physics and geography. Currents may be referred to according to their forcing mechanism as either **wind driven** or **thermohaline**. Alternatively, they may be classified according to their depth (surface, intermediate, deep or bottom). The surface circulation of the world ocean is mostly wind driven. Thermohaline currents are driven by differences in heat and salt and are associated with the sinking of dense water at high latitudes; the currents driven by thermohaline forcing are typically subsurface. Note that this classification scheme is not unambiguous; the circumpolar current, which is wind driven, extends from the surface to the bottom.

A **periodic current** is one for which the speed or direction changes cyclically at somewhat regular intervals, such as a tidal current. A **seasonal current** is one which changes in speed or direction due to seasonal winds. The mean circulation of the ocean consists of semi-permanent currents which experience relatively little periodic or seasonal change.

A **coastal current** flows roughly parallel to a coast, outside the surf zone, while a **longshore current** is one parallel to a shore, inside the surf zone, generated by waves striking the beach at an angle. Any current some distance from the shore may be called an **offshore current**, and one close to the shore an **inshore current**.

3201. Causes Of Ocean Currents

The primary generating forces are wind and differences in density of the water caused by variations in heat and salt. Currents generated by these forces are modified by such factors as depth of water, underwater topography including shape of the basin in which the current is running, extent and location of land, and deflection by the rotation of the earth.

3202. Wind Driven Currents

The stress of wind blowing across the sea causes a surface layer of water to move. Due to the low viscosity of water, this stress is not directly communicated to the ocean interior, but is balanced by the Coriolis force within a relatively thin surface layer, 10-200m thick. This layer is called the **Ekman layer** and the motion of this layer is called the **Ekman transport**. Because of the deflection by the Coriolis force, the Ekman transport is not in the direction of the wind, but is 90° to the right in the Northern Hemisphere and 90° toward the left in the Southern Hemisphere. The amount of water flowing in this layer depends only upon the wind and the Coriolis force and is independent of the depth of the Ekman layer and the viscosity of the water.

The large scale convergence or divergence of Ekman transport serves to drive the general ocean circulation. Consider the case of the Northern Hemisphere subtropics. To the south lie easterly winds with associated northward Ekman transport. To the north lie westerly winds with southward Ekman transport. The convergence of these Ekman transports is called **Ekman pumping** and results in a thickening of the upper ocean and a increase in the depth of the thermocline. The resulting subsurface pressure gradients, balanced by the Coriolis force, give rise to the anticyclonic subtropical gyres found at mid latitudes in each ocean basin. In subpolar regions, Ekman suction produces cyclonic gyres.

These wind driven gyres are not symmetrical. Along the western boundary of the oceans, currents are narrower, stronger, and deeper, often following a meandering course. These currents are sometimes called a **stream**. In contrast, currents in mid-ocean and at the eastern boundary, are often broad, shallow and slow-moving. Sometimes these are called **drift currents**.

Within the Ekman layer, the currents actually form a spiral. At the surface, the difference between wind direction and surface wind-current direction varies from about 15° along shallow coastal areas to a maximum of 45° in the deep oceans. As the motion is transmitted to successively deep layers, the Coriolis force continues to deflect the current. At

the bottom of the Ekman layer, the current flows in the opposite direction to the surface current. This shift of current directions with depth, combined with the decrease in velocity with depth, is called the **Ekman spiral**.

The velocity of the surface current is the sum of the velocities of the Ekman, geostrophic, tidal, and other currents. The Ekman surface current or wind drift current depends upon the speed of the wind, its constancy, the length of time it has blown, and other factors. In general, however, wind drift current is about 2 percent of the wind speed, or a little less, in deep water where the wind has been blowing steadily for at least 12 hours.

3203. Currents Related To Density Differences

The density of water varies with salinity, temperature, and pressure. At any given depth, the differences in density are due only to differences in temperature and salinity. With sufficient data, maps showing geographical density distribution at a certain depth can be drawn, with lines connecting points of equal density. These lines would be similar to isobars on a weather map and serve an analogous purpose, showing areas of high density and those of low density. In an area of high density, the water surface is lower than in an area of low density, the maximum difference in height being about 1 meter in 100 km. Because of this difference, water tends to flow from an area of higher water (low density) to one of lower water (high density). But due to rotation of the earth, it is deflected by the Coriolis force or toward the right in the Northern Hemisphere, and toward the left in the Southern Hemisphere. This balance, between subsurface pressure fields and the Coriolis force, is called **geostrophic equilibrium**. At a given latitude, the greater the density gradient (rate of change with distance), the faster the geostrophic current.

OCEANIC CIRCULATION

3204. Introduction

A number of ocean currents flow with great persistence, setting up a circulation that continues with relatively little change throughout the year. Because of the influence of wind in creating current, there is a relationship between this oceanic circulation and the general circulation of the atmosphere. The oceanic circulation is shown on the chart following this page (winter N. hemisphere), with the names of the major ocean currents. Some differences in opinion exist regarding the names and limits of some of the currents, but those shown are representative. Speed may vary somewhat with the season. This is particularly noticeable in the Indian Ocean and along the South China coast, where currents are influenced to a marked degree by the monsoons.

3205. Southern Ocean Currents

The Southern Ocean has no meridional boundaries and its waters are free to circulate around the world. It serves as a conveyor belt for the other oceans, exchanging waters between them. The northern boundary of the Southern Ocean is marked by the Subtropical Convergence zone. This zone marks the transition from the temperate region of the ocean to the polar region and is associated with the surfacing of the main thermocline. This zone is typically found at 40°S but varies with longitude and season.

In the Antarctic, the circulation is generally from west to east in a broad, slow-moving current extending completely around Antarctica. This is called the **Antarctic Circumpolar Current** or the **West Wind Drift**, and it is formed partly by the strong westerly wind in this area, and partly by density differences. This current is augmented by the Brazil and Falkland Currents in the Atlantic, the East Australia Current in the Pacific, and the Agulhas Current in the Indian Ocean. In return, part of it curves northward to form the Cape Horn, Falkland, and most of the Benguela Currents in the Atlantic, and the Peru Current in the Pacific.

In a narrow zone next to the Antarctic continent, a westward flowing coastal current is usually found. This current is called the **East Wind Drift** because it is attributed to the prevailing easterly winds which occur there.

3206. Atlantic Ocean Currents

The trade winds set up a system of equatorial currents which at times extends over as much as 50° of latitude or more. There are two westerly flowing currents conforming generally with the areas of trade winds, separated by a weaker, easterly flowing countercurrent.

The **North Equatorial Current** originates to the northward of the Cape Verde Islands and flows almost due west at an average speed of about 0.7 knot.

The **South Equatorial Current** is more extensive. It starts off the west coast of Africa, south of the Gulf of Guinea, and flows in a generally westerly direction at an average speed of about 0.6 knot. However, the speed gradually increases until it may reach a value of 2.5 knots, or more, off the east coast of South America. As the current approaches Cabo de Sao Roque, the eastern extremity of South America, it divides, the southern part curving toward the south along the coast of Brazil, and the northern part being deflected northward by the continent of South America.

Between the North and South Equatorial Currents, the weaker **North Equatorial Countercurrent** sets toward the east in the general vicinity of the doldrums. This is fed by

water from the two westerly flowing equatorial currents, particularly the South Equatorial Current. The extent and strength of the Equatorial Countercurrent changes with the seasonal variations of the wind. It reaches a maximum during July and August, when it extends from about 50° west longitude to the Gulf of Guinea. During its minimum, in December and January, it is of very limited extent, the western portion disappearing altogether.

That part of the South Equatorial Current flowing along the northern coast of South America which does not feed the Equatorial Countercurrent unites with the North Equatorial Current at a point west of the Equatorial Countercurrent. A large part of the combined current flows through various passages between the Windward Islands and into the Caribbean Sea. It sets toward the west, and then somewhat north of west, finally arriving off the Yucatan peninsula. From there, the water enters the Gulf of Mexico and forms the **Loop Current**; the path of the Loop Current is variable with a 13-month period. It begins by flowing directly from Yucatan to the Florida Straits, but gradually grows to flow anticyclonically around the entire Eastern Gulf; it then collapses, again following the direct path from Yucatan to the Florida Straits, with the loop in the Eastern Gulf becoming a separate eddy which slowly flows into the Western Gulf.

Within the Straits of Florida, the Loop Current feeds the beginnings of the most remarkable of American ocean currents, the **Gulf Stream**. Off the southeast coast of Florida this current is augmented by the **Antilles Current** which flows along the northern coasts of Puerto Rico, Hispaniola, and Cuba. Another current flowing eastward of the Bahamas joins the stream north of these islands.

The Gulf Stream follows generally along the east coast of North America, flowing around Florida, northward and then northeastward toward Cape Hatteras, and then curving toward the east and becoming broader and slower. After passing the Grand Banks, it turns more toward the north and becomes a broad drift current flowing across the North Atlantic. The part in the Straits of Florida is sometimes called the **Florida Current**.

A tremendous volume of water flows northward in the Gulf Stream. It can be distinguished by its deep indigo-blue color, which contrasts sharply with the dull green of the surrounding water. It is accompanied by frequent squalls. When the Gulf Stream encounters the cold water of the Labrador Current, principally in the vicinity of the Grand Banks, there is little mixing of the waters. Instead, the junction is marked by a sharp change in temperature. The line or surface along which this occurs is called the **cold wall**. When the warm Gulf Stream water encounters cold air, evaporation is so rapid that the rising vapor may be visible as frost smoke.

Investigations have shown that the current itself is much narrower and faster than previously supposed, and considerably more variable in its position and speed. The maximum current off Florida ranges from about 2 to 4 knots. Northward, the speed is generally less, and it decreases further after the current passes Cape Hatteras. As the stream meanders and shifts position, eddies sometimes break off and continue as separate, circular flows until they dissipate. Boats in the Newport-Bermuda sailing yacht race have been known to be within sight of each other and be carried in opposite directions by different parts of the same current. This race is generally won by the boat which catches an eddy just right. As the current shifts position, its extent does not always coincide with the area of warm, blue water. When the sea is relatively smooth, the edges of the current are marked by ripples.

A recirculation region exists adjacent to and southwest of the Gulf Stream. The flow of water in the recirculation region is opposite to that in the Gulf Stream and surface currents are much weaker, generally less than half a knot.

As the Gulf Stream continues eastward and northeastward beyond the Grand Banks, it gradually widens and decreases speed until it becomes a vast, slow-moving current known as the **North Atlantic Current**, in the general vicinity of the prevailing westerlies. In the eastern part of the Atlantic it divides into the **Northeast Drift Current** and the **Southeast Drift Current**.

The Northeast Drift Current continues in a generally northeasterly direction toward the Norwegian Sea. As it does so, it continues to widen and decrease speed. South of Iceland it branches to form the **Irminger Current** and the **Norway Current**. The Irminger Current curves toward the north and northwest to join the East Greenland Current southwest of Iceland. The Norway Current continues in a northeasterly direction along the coast of Norway. Part of it, the **North Cape Current**, rounds North Cape into the Barents Sea. The other part curves toward the north and becomes known as the **Spitsbergen Current**. Before reaching Svalbard (Spitsbergen), it curves toward the west and joins the cold **East Greenland Current** flowing southward in the Greenland Sea. As this current flows past Iceland, it is further augmented by the Irminger Current.

Off Kap Farvel, at the southern tip of Greenland, the East Greenland Current curves sharply to the northwest following the coastline. As it does so, it becomes known as the **West Greenland Current**, and its character changes from that of an intense western boundary current to a weaker eastern boundary current. This current continues along the west coast of Greenland, through Davis Strait, and into Baffin Bay.

In Baffin Bay the West Greenland Current generally follows the coast, curving westward off Kap York to form the southerly flowing **Labrador Current**. This cold current flows southward off the coast of Baffin Island, through Davis Strait, along the coast of Labrador and Newfoundland, to the Grand Banks, carrying with it large quantities of ice. Here it encounters the warm water of the Gulf Stream, creating the cold wall. Some of the cold water flows southward along the east coast of North America, inshore of the Gulf Stream, as far as Cape Hatteras. The remainder curves toward the east and flows along the northern edge of the North Atlantic and Northeast Drift Currents,

gradually merging with them.

The **Southeast Drift Current** curves toward the east, southeast, and then south as it is deflected by the coast of Europe. It flows past the Bay of Biscay, toward southeastern Europe and the Canary Islands, where it continues as the **Canary Current**. In the vicinity of the Cape Verde Islands, this current divides, part of it curving toward the west to help form the **North Equatorial Current**, and part of it curving toward the east to follow the coast of Africa into the Gulf of Guinea, where it is known as the **Guinea Current**. This current is augmented by the **North Equatorial Countercurrent** and, in summer, it is strengthened by monsoon winds. It flows in close proximity to the South Equatorial Current, but in the opposite direction. As it curves toward the south, still following the African coast, it merges with the South Equatorial Current.

The clockwise circulation of the North Atlantic leaves a large central area between the recirculation region and the Canary Current which has no well-defined currents. This area is known as the **Sargasso Sea**, from the large quantities of sargasso or gulfweed encountered there.

That branch of the South Equatorial Current which curves toward the south off the east coast of South America, follows the coast as the warm, highly-saline **Brazil Current**, which in some respects resembles a weak Gulf Stream. Off Uruguay it encounters the colder, less-salty **Falkland** or **Malvinas Current** forming a sharp meandering front in which eddies may form. The two currents curve toward the east to form the broad, slow-moving, **South Atlantic Current** in the general vicinity of the prevailing westerlies and the front dissipates somewhat. This current flows eastward to a point west of the Cape of Good Hope, where it curves northward to follow the west coast of Africa as the strong **Benguela Current**, augmented somewhat by part of the **Agulhas Current** flowing around the southern part of Africa from the Indian Ocean. As it continues northward, the current gradually widens and slows. At a point east of St. Helena Island it curves westward to continue as part of the South Equatorial Current, thus completing the counterclockwise circulation of the South Atlantic. The Benguela Current is also augmented somewhat by the West Wind Drift, a current which flows easterly around Antarctica. As the West Wind Drift flows past Cape Horn, that part in the immediate vicinity of the cape is called the **Cape Horn Current**. This current rounds the cape and flows in a northerly and northeasterly direction along the coast of South America as the Falkland or Malvinas Current.

3207. Pacific Ocean Currents

Pacific Ocean currents follow the general pattern of those in the Atlantic. The **North Equatorial Current** flows westward in the general area of the northeast trades, and the **South Equatorial Current** follows a similar path in the region of the southeast trades. Between these two, the weaker **North Equatorial Countercurrent** sets toward the east, just north of the equator.

After passing the Mariana Islands, the major part of the North Equatorial Current curves somewhat toward the northwest, past the Philippines and Taiwan. Here it is deflected further toward the north, where it becomes known as the **Kuroshio**, and then toward the northeast past the Nansei Shoto and Japan, and on in a more easterly direction. Part of the Kuroshio, called the **Tsushima Current**, flows through Tsushima Strait, between Japan and Korea, and the Sea of Japan, following generally the northwest coast of Japan. North of Japan it curves eastward and then southeastward to rejoin the main part of the Kuroshio. The limits and volume of the Kuroshio are influenced by the monsoons, being augmented during the season of southwesterly winds, and diminished when the northeasterly winds are prevalent.

The Kuroshio (Japanese for “Black Stream”) is so named because of the dark color of its water. It is sometimes called the **Japan Current**. In many respects it is similar to the Gulf Stream of the Atlantic. Like that current, it carries large quantities of warm tropical water to higher latitudes, and then curves toward the east as a major part of the general clockwise circulation in the Northern Hemisphere. As it does so, it widens and slows, continuing on between the Aleutians and the Hawaiian Islands, where it becomes known as the **North Pacific Current**.

As this current approaches the North American continent, most of it is deflected toward the right to form a clockwise circulation between the west coast of North America and the Hawaiian Islands called the **California Current**. This part of the current has become so broad that the circulation is generally weak. Near the coast, the southeastward flow intensifies and average speeds are about 0.8 knot. But the flow pattern is complex, with offshore directed jets often found near more prominent capes, and poleward flow often found over the upper slope and outer continental shelf. It is strongest near land. Near the southern end of Baja California, this current curves sharply to the west and broadens to form the major portion of the North Equatorial Current.

During the winter, a weak countercurrent flows northwestward, inshore of the southeastward flowing California Current, along the west coast of North America from Baja California to Vancouver Island. This is called the **Davidson Current**.

Off the west coast of Mexico, south of Baja California the current flows southeastward during the winter as a continuation of part of the California Current. During the summer, the current in this area is northwestward as a continuation of the North Equatorial Countercurrent.

As in the Atlantic, there is in the Pacific a counterclockwise circulation to the north of the clockwise circulation. Cold water flowing southward through the western part of Bering Strait between Alaska and Siberia, is joined by water circulating counterclockwise in the Bering Sea to form the **Oyashio**. As the current leaves the strait, it curves toward the right and flows southwesterly along the coast of Siberia and the Kuril Islands. This current brings quantities of sea ice, but no icebergs. When it encounters the Kuroshio, the

Oyashio curves southward and then eastward, the greater portion joining the Kuroshio and North Pacific Current.

The northern branch of the North Pacific Current curves in a counterclockwise direction to form the **Alaska Current**, which generally follows the coast of Canada and Alaska. When the Alaska Current turns to the southwest and flows along the Kodiak Island and the Alaska Peninsula, its character changes to that of a western boundary current and it is called the Alaska Stream. When this westward flow arrives off the Aleutian Islands, it is less intense and becomes known as the **Aleutian Current**. Part of it flows along the southern side of these islands to about the 180th meridian, where it curves in a counterclockwise direction and becomes an easterly flowing current, being augmented by the northern part of the Oyashio. The other part of the Aleutian Current flows through various openings between the Aleutian Islands, into the Bering Sea. Here it flows in a general counterclockwise direction. The southward flow along the Kamchatka peninsula is called the **Kamchatka Current** which feeds the southerly flowing Oyashio. Some water flows northward from the Bering Sea through the eastern side of the Bering Strait, into the Arctic Ocean.

The **South Equatorial Current**, extending in width between about 4°N latitude and 10°S, flows westward from South America to the western Pacific. After this current crosses the 180th meridian, the major part curves in a counterclockwise direction, entering the Coral Sea, and then curving more sharply toward the south along the east coast of Australia, where it is known as the **East Australian Current**. The East Australian Current is the weakest of the subtropical western boundary currents and separates from the Australian coast near 34°S. The path of the current from Australia to New Zealand is known as the **Tasman Front**, which marks the boundary between the warm water of the Coral Sea and the colder water of the Tasman Sea. The continuation of the East Australian Current east of New Zealand is the **East Auckland Current**. The East Auckland Current varies seasonally: in winter, it separates from the shelf and flows eastward, merging with the West Wind Drift, while in winter it follows the New Zealand shelf southward as the **East Cape Current** until it reaches Chatham Rise where it turns eastward, thence merging with the West Wind Drift.

Near the southern extremity of South America, most of this current flows eastward into the Atlantic, but part of it curves toward the left and flows generally northward along the west coast of South America as the **Peru Current** or **Humboldt Current**. Occasionally a set directly toward land is encountered. At about Cabo Blanco, where the coast falls away to the right, the current curves toward the left, past the Galapagos Islands, where it takes a westerly set and constitutes the major portion of the South Equatorial Current, thus completing the counterclockwise circulation of the South Pacific.

During the northern hemisphere summer, a weak northern branch of the South Equatorial Current, known as the **New Guinea Coastal Current**, continues on toward the west and northwest along both the southern and northeastern coasts of New Guinea. The southern part flows through Torres Strait, between New Guinea and Australia, into the Arafura Sea. Here, it gradually loses its identity, part of it flowing on toward the west as part of the South Equatorial Current of the Indian Ocean, and part of it following the coast of Australia and finally joining the easterly flowing West Wind Drift. The northern part of New Guinea Coastal Current both curves in a clockwise direction to help form the Pacific Equatorial Countercurrent and off Mindanao turns southward to form a southward flowing boundary current called the **Mindanao Current**. During the northern hemisphere winter, the New Guinea Coastal Current may reverse direction for a few months.

3208. Indian Ocean Currents

Indian Ocean currents follow generally the pattern of the Atlantic and Pacific but with differences caused principally by the monsoons, the more limited extent of water in the Northern Hemisphere, and by limited communication with the Pacific Ocean along the eastern boundary. During the northern hemisphere winter, the **North Equatorial Current** and **South Equatorial Current** flow toward the west, with the weaker, eastward **Equatorial Countercurrent** flowing between them, as in the Atlantic and Pacific (but somewhat south of the equator). But during the northern hemisphere summer, both the North Equatorial Current and the Equatorial Countercurrent are replaced by the **Southwest Monsoon Current**, which flows eastward and southeastward across the Arabian Sea and the Bay of Bengal. Near Sumatra, this current curves in a clockwise direction and flows westward, augmenting the South Equatorial Current, and setting up a clockwise circulation in the northern part of the Indian Ocean. Off the coast of Somalia, the **Somali Current** reverses direction during the northern hemisphere summer with northward currents reaching speeds of 5 knots or more. Twice a year, around May and November, westerly winds along the equator result in an eastward **Equatorial Jet** which feeds warm water towards Sumatra.

As the South Equatorial Current approaches the coast of Africa, it curves toward the southwest, part of it flowing through the Mozambique Channel between Madagascar and the mainland, and part flowing along the east coast of Madagascar. At the southern end of this island the two join to form the strong **Agulhas Current**, which is analogous to the Gulf Stream. This current, when opposed by strong winds from Southern Ocean storms, creates dangerously large seas.

South of South Africa, the Agulhas Current retroflects, and most of the flow curves sharply southward and then eastward to join the West Wind Drift; this junction is often marked by a broken and confused sea, made much worse by westerly storms. A small part of the Agulhas Current rounds the southern end of Africa and helps form the **Benguela Current**; occasionally, strong eddies are formed in the retroflection region and these too move into the Southeastern Atlantic.

The eastern boundary currents in the Indian Ocean are quite different from those found in the Atlantic and Pacific. The seasonally reversing **South Java Current** has strongest westward flow during August when monsoon winds are easterly and the Equatorial jet is inactive. Along the coast of Australia, a vigorous poleward flow, the **Leeuwin Current**, runs against the prevailing winds.

3209. Arctic Currents

The waters of the North Atlantic enter the Arctic Ocean between Norway and Svalbard. The currents flow easterly, north of Siberia, to the region of the Novosibirskiye Ostrova, where they turn northerly across the North Pole, and continue down the Greenland coast to form the **East Greenland Current**. On the American side of the Arctic basin, there is a weak, continuous clockwise flow centered in the vicinity of 80°N, 150°W. A current north through Bering Strait along the American coast is balanced by an outward southerly flow along the Siberian coast, which eventually becomes part of the **Kamchatka Current**. Each of the main islands or island groups in the Arctic, as far as is known, seems to have a clockwise nearshore circulation around it. The Barents Sea, Kara Sea, and Laptev Sea each have a weak counterclockwise circulation. A similar but weaker counterclockwise current system appears to exist in the East Siberian Sea.

OCEANIC CURRENT PHENOMENA

3210. Ocean Eddies And Rings

Eddies with horizontal diameters varying from 50-150 km have their own pattern of surface currents. These features may have either a warm or a cold core and currents flow around this core, either cyclonically for cold cores or anticyclonically for warm cores. The most intense of these features are called **rings** and are formed by the pinching off of meanders of western boundary currents such as the Gulf Stream. Maximum speed associated with these features is about 2 knots. Rings have also been observed to pinch off from the Agulhas retroflexion and to then drift to the northwest into the South Atlantic. Similarly, strong anticyclonic eddies are occasionally spawned by the loop current into the Western Gulf Mexico.

In general, mesoscale variability is strongest in the region of western boundary currents and in the Circumpolar Current. The strength of mesoscale eddies is greatly reduced at distances of 200-400 km from these strong boundary currents, because mean currents are generally weaker in these regions. The eddies may be sufficiently strong to reverse the direction of the surface currents.

3211. Undercurrents

At the equator and along some ocean boundaries, shallow undercurrents exist, flowing in a direction counter to that at the surface. These currents may affect the operation of submarines or trawlers. The most intense of these flows, called the Pacific **Equatorial Undercurrent**, is found at the equator in the Pacific. It is centered at a depth of 150m to the west of the Galapagos, is about 4 km wide, and eastward speeds of up to 1.5 m/s have been observed. Equatorial Undercurrents are also observed in the Atlantic and Indian Ocean, but they are somewhat weaker. In the Atlantic, the Equatorial Undercurrent is found to the east of 24°W and in the Indian Ocean, it appears to be seasonal.

Undercurrents also exist along ocean boundaries. They seem to be most ubiquitous at the eastern boundary of oceans. Here they are found at depths of 100-200m, may be 100 km wide, and have maximum speeds of 0.5 m/s.

3212. Ocean Currents And Climate

Many of the ocean currents exert a marked influence upon the climate of the coastal regions along which they flow. Thus, warm water from the Gulf Stream, continuing as the North Atlantic, Northeast Drift, and Irminger Currents, arrives off the southwest coast of Iceland, warming it to the extent that Reykjavik has a higher average winter temperature than New York City, far to the south. Great Britain and Labrador are about the same latitude, but the climate of Great Britain is much milder because of the relatively warm currents. The west coast of the United States is cooled in the summer by the California Current, and warmed in the winter by the Davidson Current. Partly as a result of this circulation, the range of monthly average temperature is comparatively small.

Currents exercise other influences besides those on temperature. The pressure pattern is affected materially, as air over a cold current contracts as it is cooled, and that over a warm current expands. As air cools above a cold ocean current, fog is likely to form. Frost smoke occurs over a warm current which flows into a colder region. Evaporation is greater from warm water than from cold water, adding to atmospheric moisture.

3213. Ocean Current Observations

Historically, our views of the surface circulation of the ocean have been shaped by reports of ocean currents provided by mariners. As mentioned at the start of this chapter, these observations consist of reports of the difference between the dead reckoning and the observed position of the vessel. These observations were routinely collected until the start of World War II.

Two observation systems are generally used for surface current studies. The first utilizes autonomous free-drifting

buoys which are tracked by satellite or relay their position via satellite. These buoys consist of either a spherical or cylindrical surface float which is about 0.5m in diameter with a drogue at a depth of about 35m. The second system utilizes acoustic Doppler current profilers. These profilers utilize hull mounted transducers, operate at a frequency of 150 kHz, and have pulse repetition rates of about 1 second. They can penetrate to about 300m, and, where water is shallower than this depth, track the bottom. Merchant and naval vessels are increasingly being outfitted with acoustic Doppler current profilers which, when operated with the Global Positioning System, provide accurate observations of currents.

CHAPTER 33

WAVES, BREAKERS AND SURF

OCEAN WAVES

3300. Introduction

Ocean Waves are the most widely observed phenomenon at sea, and possibly the least understood by the average seaman. More than any other single factor, ocean waves are likely to cause a navigator to change course or speed to avoid damage to ship and cargo. Wind-generated ocean waves have been measured at more than 100 feet high, and tsunamis, caused by earthquakes, far higher. A mariner with knowledge of basic facts concerning waves is able to use them to his advantage, avoid hazardous conditions, and operate with a minimum of danger if such conditions cannot be avoided. See Chapter 38, Weather Routing, for details on how to avoid areas of severe waves.

3301. Causes Of Waves

Waves on the surface of the sea are caused principally by wind, but other factors, such as submarine earthquakes, volcanic eruptions, and the tide, also cause waves. If a breeze of less than 2 knots starts to blow across smooth water, small wavelets called **ripples** form almost instantaneously. When the breeze dies, the ripples disappear as suddenly as they formed, the level surface being restored by surface tension of the water. If the wind speed exceeds 2 knots, more stable **gravity waves** gradually form, and progress with the wind.

While the generating wind blows, the resulting waves may be referred to as **sea**. When the wind stops or changes direction, waves that continue on without relation to local winds are called **swell**.

Unlike wind and current, waves are not deflected appreciably by the rotation of the earth, but move in the direction in which the generating wind blows. When this wind ceases, friction and spreading cause the waves to be reduced in height, or attenuated, as they move. However, the reduction takes place so slowly that swell often continues until it reaches some obstruction, such as a shore.

The Fleet Numerical Meteorology and Oceanography Center produces synoptic analyses and predictions of ocean wave heights using a spectral numerical model. The wave information consists of heights and directions for different periods and wavelengths. Verification of projected data has proven the model to be very good. Information from the model is provided to the U.S. Navy on a routine basis and is a vital input to the Optimum Track Ship Routing program.

3302. Wave Characteristics

Ocean waves are very nearly in the shape of an inverted cycloid, the figure formed by a point inside the rim of a wheel rolling along a level surface. This shape is shown in Figure 3302a. The highest parts of waves are called **crests**, and the intervening lowest parts, troughs. Since the crests are steeper and narrower than the troughs, the mean or still water level is a little lower than halfway between the crests and troughs. The vertical distance between trough and crest is called **wave height**, labeled H in Figure 3302a. The horizontal distance between successive crests, measured in the direction of travel, is called **wavelength**, labeled L. The time interval between passage of successive crests at a stationary point is called **wave period** (P). Wave height, length, and period depend upon a number of factors, such as the wind speed, the length of time it has blown, and its **fetch** (the straight distance it has traveled over the surface). Table 3302 indicates the relationship between wind speed, fetch, length of time the wind blows, wave height, and wave period in deep water.

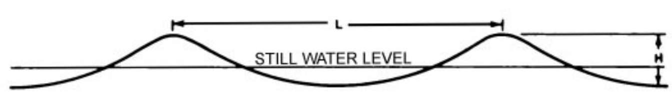


Figure 3302a. A typical sea wave

If the water is deeper than one-half the wavelength (L), this length in feet is theoretically related to period (P) in seconds by the formula:

$$L = 5.12\ P^2.$$

The actual value has been found to be a little less than this for swell, and about two-thirds the length determined by this formula for sea. When the waves leave the generating area and continue as free waves, the wavelength and period continue to increase, while the height decreases. The rate of change gradually decreases.

Fetch	BEAUFORT NUMBER 3			4			5			6			7			8			9			10			11			Fetch
	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	T	H	P	
10	4.4	1.8	2.1	3.7	2.6	2.4	3.2	3.5	2.8	2.7	5.0	3.1	2.5	6.0	3.4	2.3	7.3	3.9	2.0	8.0	4.1	1.9	10.0	4.2	1.8	10.0	5.0	10
20	7.1	2.0	2.5	6.2	3.2	2.9	5.4	4.9	3.3	4.7	7.0	3.8	4.2	8.6	4.3	3.9	10.0	4.4	3.5	12.0	5.0	3.2	14.0	5.2	3.0	16.0	5.9	20
30	9.8	2.0	2.8	8.3	3.8	3.3	7.2	5.8	3.7	6.2	8.0	4.2	5.8	10.0	4.6	5.2	12.1	5.0	4.7	15.8	5.5	4.4	18.0	6.0	4.1	19.8	6.3	30
40	12.0	2.0	3.0	10.3	3.9	3.6	8.9	6.2	4.1	7.8	9.0	4.6	7.1	11.2	4.9	6.5	14.0	5.4	5.8	17.7	5.9	5.4	21.0	6.3	5.1	22.5	6.7	40
50	14.0	2.0	3.2	12.4	4.0	3.8	11.0	6.5	4.4	9.1	9.8	4.8	8.4	12.2	5.2	7.7	15.7	5.6	6.9	19.8	6.3	6.4	23.0	6.7	6.1	25.0	7.1	50
60	16.0	2.0	3.5	14.0	4.0	4.0	12.0	6.8	4.6	10.2	10.3	5.1	9.6	13.2	5.5	8.7	17.0	6.0	8.0	21.0	6.5	7.4	25.0	7.0	7.0	27.5	7.5	60
70	18.0	2.0	3.7	15.8	4.0	4.1	13.5	7.0	4.8	11.9	10.8	5.4	10.5	13.9	5.7	9.9	18.0	6.4	9.0	22.5	6.8	8.3	26.5	7.3	7.8	29.5	7.7	70
80	20.0	2.0	3.8	17.0	4.0	4.2	15.0	7.2	4.9	13.0	11.0	5.6	12.0	14.5	6.0	11.0	18.9	6.6	10.0	24.0	7.1	9.3	28.0	7.7	8.6	31.5	7.9	80
90	23.6	2.0	3.9	18.8	4.0	4.3	16.5	7.3	5.1	14.1	11.2	5.8	13.0	15.0	6.3	12.0	20.0	6.7	11.0	25.0	7.2	10.2	30.0	7.9	9.5	34.0	8.2	90
100	27.1	2.0	4.0	20.0	4.0	4.4	17.5	7.3	5.3	15.1	11.4	6.0	14.0	15.5	6.5	12.8	20.5	6.9	11.9	26.5	7.6	11.0	32.0	8.1	10.3	35.0	8.5	100
120	31.1	2.0	4.2	22.4	4.1	4.7	20.0	7.8	5.4	17.0	11.7	6.2	15.9	16.0	6.7	14.5	21.5	7.3	13.1	27.5	7.9	12.3	33.5	8.4	11.5	37.5	8.8	120
140	36.6	2.0	4.5	25.8	4.2	4.9	22.5	7.9	5.8	19.1	11.9	6.4	17.6	16.2	7.0	16.0	22.0	7.6	14.8	29.0	8.3	13.9	35.5	8.8	13.0	40.0	9.2	140
160	43.2	2.0	4.9	28.4	4.2	5.2	24.3	7.9	6.0	21.1	12.0	6.6	19.5	16.5	7.3	18.0	23.0	8.0	16.4	30.5	8.7	15.1	37.0	9.1	14.5	42.5	9.6	160
180	50.0	2.0	4.9	30.9	4.3	5.4	27.0	8.0	6.2	23.1	12.1	6.8	21.3	17.0	7.5	19.9	23.5	8.3	18.0	31.5	9.0	16.5	38.5	9.5	16.0	44.5	10.0	180
200				33.5	4.3	5.6	29.0	8.0	6.4	25.4	12.2	7.1	23.1	17.5	7.7	21.5	23.5	8.5	19.3	32.5	9.2	18.1	40.0	9.8	17.1	46.0	10.3	200
220				36.5	4.4	5.8	31.1	8.0	6.6	27.2	12.3	7.2	25.0	17.9	8.0	22.9	24.0	8.8	20.9	34.0	9.6	19.1	41.5	10.1	18.2	47.5	10.6	220
240				39.2	4.4	5.9	33.1	8.0	6.8	29.0	12.4	7.3	26.8	17.9	8.2	24.4	24.5	9.0	22.0	34.5	9.8	20.5	43.0	10.3	19.5	49.0	10.8	240
260				41.9	4.4	6.0	34.9	8.0	6.9	30.5	12.6	7.5	28.0	18.0	8.4	26.0	25.0	9.2	23.5	34.5	10.0	21.8	44.0	10.6	20.9	50.5	11.1	260
280				44.5	4.4	6.2	36.8	8.0	7.0	32.4	12.9	7.8	29.5	18.0	8.5	27.7	25.0	9.4	25.0	35.0	10.2	23.0	45.0	10.9	22.0	51.5	11.3	280
300				47.0	4.4	6.3	38.5	8.0	7.1	34.1	13.1	8.0	31.5	18.0	8.7	29.0	25.0	9.5	26.3	35.0	10.4	24.3	45.0	11.1	23.2	53.0	11.6	300
320							40.5	8.0	7.2	36.0	13.3	8.2	33.0	18.0	8.9	30.2	25.0	9.6	27.6	35.5	10.6	25.5	45.5	11.2	24.5	54.0	11.8	320
340							42.4	8.0	7.3	37.6	13.4	8.3	34.2	18.0	9.0	31.6	25.0	9.8	29.0	36.0	10.8	26.7	46.0	11.4	25.5	55.0	12.0	340
360							44.2	8.0	7.4	38.8	13.4	8.4	35.7	18.1	9.1	33.0	25.0	9.9	30.0	36.5	10.9	27.7	46.5	11.6	26.6	55.0	12.2	360
380							46.1	8.0	7.5	40.2	13.5	8.5	37.1	18.2	9.3	34.2	25.5	10.0	31.3	37.0	11.1	29.1	47.0	11.8	27.7	55.5	12.4	380
400							48.0	8.0	7.7	42.2	13.5	8.6	38.8	18.4	9.5	35.6	26.0	10.2	32.5	37.0	11.2	30.2	47.5	12.0	28.9	56.0	12.6	400
420							50.0	8.0	7.8	43.5	13.6	8.7	40.0	18.7	9.6	36.9	26.5	10.3	33.7	37.5	11.4	31.5	47.5	12.2	29.6	56.5	12.7	420
440							52.0	8.0	7.9	44.7	13.7	8.8	41.3	18.8	9.7	38.1	27.0	10.4	34.8	37.5	11.5	32.5	48.0	12.3	30.9	57.0	12.9	440
460							54.0	8.0	8.0	46.2	13.7	8.9	42.8	19.0	9.8	39.5	27.5	10.6	36.0	37.5	11.7	33.5	48.5	12.5	31.8	57.5	13.1	460
480							56.0	8.0	8.1	47.8	13.7	9.0	44.0	19.0	9.9	41.0	27.5	10.8	37.0	37.5	11.8	34.5	49.0	12.6	32.7	57.5	13.2	480
500							58.0	8.0	8.2	49.2	13.8	9.1	45.5	19.1	10.1	42.1	27.5	10.9	38.3	38.0	11.9	35.5	49.0	12.7	33.9	58.0	13.4	500
550										53.0	13.8	9.3	48.5	19.5	10.3	44.9	27.5	11.1	41.0	38.5	12.2	38.2	50.0	13.0	36.5	59.0	13.7	550
600										56.3	13.8	9.5	51.8	19.7	10.5	47.7	27.5	11.3	43.6	39.0	12.5	40.3	50.0	13.3	38.7	60.0	14.0	600
650													55.0	19.8	10.7	50.3	27.5	11.6	46.4	39.5	12.8	43.0	50.0	13.7	41.0	60.0	14.2	650
700													58.5	19.8	11.0	53.2	27.5	11.8	49.0	40.0	13.1	45.4	50.5	14.0	43.5	60.5	14.5	700
750																56.2	27.5	12.1	51.0	40.0	13.3	48.0	51.0	14.2	45.8	61.0	14.8	750
800																59.2	27.5	12.3	53.8	40.0	13.5	50.6	51.5	14.5	47.8	61.5	15.0	800
850																			56.2	40.0	13.8	52.5	52.0	14.6	50.0	62.0	15.2	850
900																			58.2	40.0	14.0	54.6	52.0	14.9	52.0	62.5	15.5	900
950																						57.2	52.0	15.1	54.0	63.0	15.7	950
1000																						59.3	52.0	15.3	56.3	63.0	16.0	1000

Table 3302. Minimum Time (T) in hours that wind must blow to form waves of H significant height (in feet) and P period (in secconds). Fetch in nautical miles.

The speed (S) of a free wave in deep water is nearly independent of its height or steepness. For swell, its relationship in knots to the period (P) in seconds is given by the formula

$$S = 3.03P.$$

The relationship for sea is not known.

The theoretical relationship between speed, wavelength, and period is shown in Figure 3302b. As waves continue on beyond the generating area, the period, wavelength, and speed remain the same. Because the waves of each period have different speeds they tend to sort themselves by periods as they move away from the generating area. The longer period waves move at a greater speed and move ahead. At great enough distances from a storm area the waves will have sorted themselves into sets based on period.

All waves are attenuated as they propagate but the short period waves attenuate faster, so that far from a storm only the longer waves remain.

The time needed for a wave system to travel a given distance is double that which would be indicated by the speed of individual waves. This is because each leading wave in succession gradually disappears and transfers its energy to following wave. The process occurs such that the whole wave *system* advances at a speed which is just half that of each individual wave. This process can easily be seen in the bow wave of a vessel. The speed at which the wave system advances is called **group velocity**.

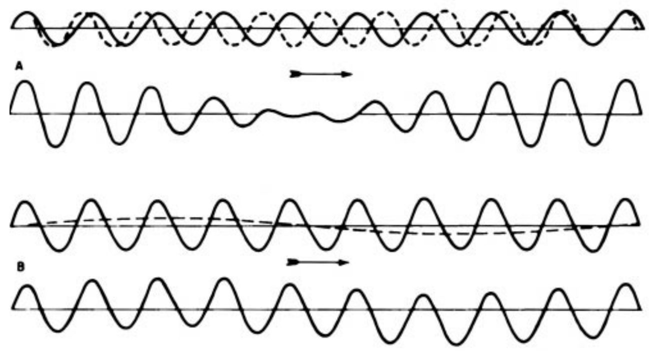


Figure 3302c. Interference. The upper part of A shows two waves of equal height and nearly equal length traveling in the same direction. The lower part of A shows the resulting wave pattern. In B similar information is shown for short waves and long swell.

Because of the existence of many independent wave systems at the same time, the sea surface acquires a complex and irregular pattern. Since the longer waves overrun the shorter ones, the resulting interference adds to the complexity of the pattern. The process of interference, illustrated in Figure 3302c, is duplicated many times in the sea; it is the principal reason that successive waves are

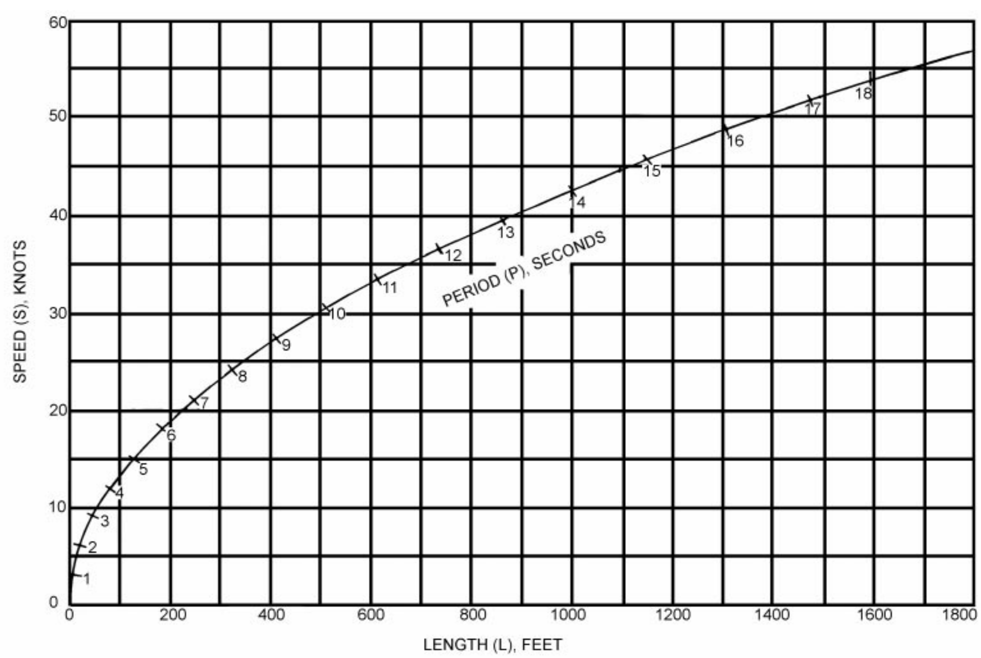


Figure 3302b. Relationship between speed, length, and period of waves in deep water, based upon the theoretical relationship between period and length.

not of the same height. The irregularity of the surface may be further accentuated by the presence of wave systems crossing at an angle to each other, producing peak-like rises.

In reporting average wave heights, the mariner has a tenency to neglect the lower ones. It has been found that the reported value is about the average for the highest one-third. This is sometimes called the "significant" wave height. The approximate relationship between this height and others, is as follows:

Wave	*Relative height*
Average	0.64
Significant	1.00
Highest 10 percent	1.29
Highest	1.87

3303. Path Of Water Particles In A Wave

As shown in Figure 3303, a particle of water on the surface of the ocean follows a somewhat circular orbit as a wave passes, but moves very little in the direction of motion of the wave. The common wave producing this action is called an **oscillatory wave**. As the crest passes, the particle moves forward, giving the water the appearance of moving with the wave. As the trough passes, the motion is in the opposite direction. The radius of the circular orbit decreases with depth, approaching zero at a depth equal to about half the wavelength. In shallower water the orbits become more elliptical, and in very shallow water the vertical motion disappears almost completely.

Since the speed is greater at the top of the orbit than at the bottom, the particle is not at exactly its original point following passage of a wave, but has moved slightly in the wave's direction of motion. However, since this advance is small in relation to the vertical displacement, a floating object is raised and lowered by passage of a wave, but moved little from its original position. If this were not so, a slow moving vessel might experience considerable difficulty in making way against a wave train. In Figure 3303 the forward displacement is greatly exaggerated.

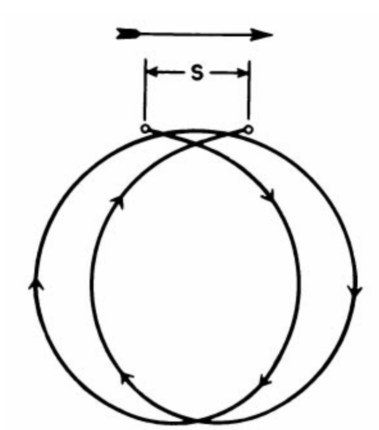


Figure 3303. Orbital motion and displacement, s, of a particle on the surface of deep water during two wave periods.

3304. Effects Of Currents On Waves

A following current increases wavelengths and decreases wave heights. An opposing current has the opposite effect, decreasing the length and increasing the height. This effect can be dangerous in certain areas of the world where a stream current opposes waves generated by severe weather. An example of this effect is off the Coast of South Africa, where the Agulhas current is often opposed by westerly storms, creating steep, dangerous seas. A strong opposing current may cause the waves to break, as in the case of **overfalls** in tidal currents. The extent of wave alteration is dependent upon the ratio of the still-water wave speed to the speed of the current.

Moderate ocean currents running at oblique angles to wave directions appear to have little effect, but strong tidal currents perpendicular to a system of waves have been observed to completely destroy them in a short period of time.

3305. The Effect Of Ice On Waves

When ice crystals form in seawater, internal friction is greatly increased. This results in smoothing of the sea surface. The effect of pack ice is even more pronounced. A vessel following a lead through such ice may be in smooth water even when a gale is blowing and heavy seas are beating against the outer edge of the pack. Hail or torrential rain is also effective in flattening the sea, even in a high wind.

3306. Waves And Shallow Water

When a wave encounters shallow water, the movement of the water is restricted by the bottom, resulting in reduced wave speed. In deep water wave speed is a function of period. In shallow water, the wave speed becomes a function of depth. The shallower the water, the slower the wave speed. As the wave speed slows, the period remains the same, so the wavelength becomes shorter. Since the energy in the waves remains the same, the shortening of wavelengths results in increased heights. This process is called **shoaling**. If the wave approaches a shallow area at an angle, each part is slowed successively as the depth decreases. This causes a change in direction of motion, or **refraction**, the wave tending to change direction parallel to the depth curves. The effect is similar to the refraction of light and other forms of radiant energy.

As each wave slows, the next wave behind it, in deeper water, tends to catch up. As the wavelength decreases, the height generally becomes greater. The lower part of a wave, being nearest the bottom, is slowed more than the top. This

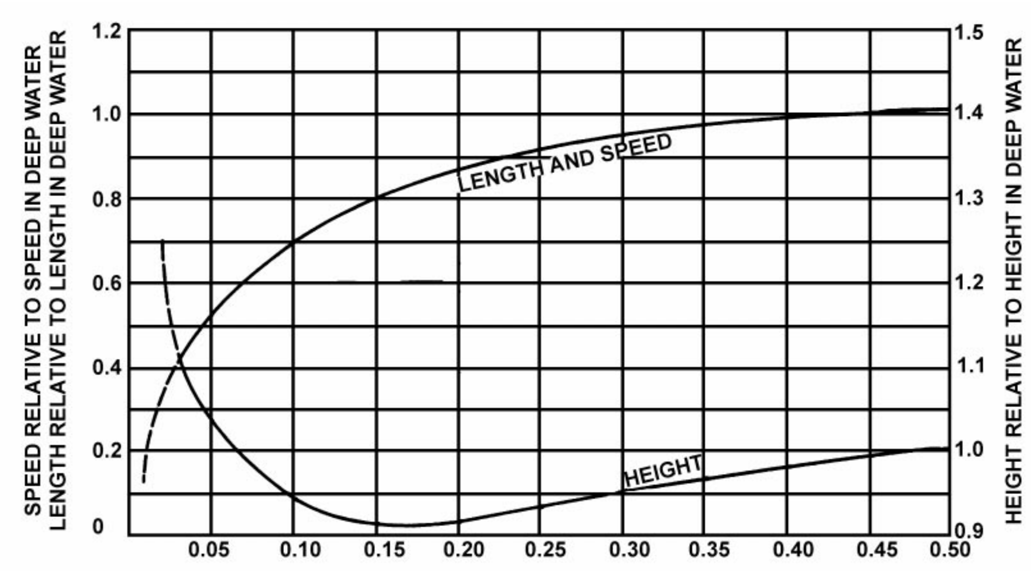


Figure 3306. Alteration of the characteristics of waves crossing a shoal.

may cause the wave to become unstable, the faster-moving top falling forward or breaking. Such a wave is called a **breaker**, and a series of breakers is **surf**.

Swell passing over a shoal but not breaking undergoes a decrease in wavelength and speed, and an increase in height, which may be sudden and dramatic, depending on the steepness of the seafloor's slope. This **ground swell** may cause heavy rolling if it is on the beam and its period is the same as the period of roll of a vessel, even though the sea may appear relatively calm. It may also cause a **rage sea**, when the swell waves encounter water shoal enough to make them break. Rage seas are dangerous to small craft, particularly approaching from seaward, as the vessel can be overwhelmed by enormous breakers in perfectly calm weather. The swell waves, of course, may have been generated hundreds of miles away. In the open ocean they are almost unnoticed due to their very long period and wavelength. Figure 3306 illustrates the approximate alteration of the characteristics of waves as they cross a shoal.

3307. Energy Of Waves

The potential energy of a wave is related to the vertical distance of each particle from its still-water position. Therefore potential energy moves with the wave. In contrast, the kinetic energy of a wave is related to the speed of the particles, distributed evenly along the entire wave.

The amount of kinetic energy in a wave is tremendous. A 4-foot, 10-second wave striking a coast expends more than 35,000 horsepower per mile of beach. For each 56 miles of coast, the energy expended equals the power generated at Hoover Dam. An increase in temperature of the water in the relatively narrow surf zone in which this energy is expended would seem to be indicated, but no pronounced increase has been measured. Apparently, any heat that may be generated is dissipated to the deeper water beyond the surf zone.

3308. Wave Measurement Aboard Ship

With suitable equipment and adequate training, reliable measurements of the height, length, period, and speed of waves can be made. However, the mariner's estimates of height and length often contain relatively large errors. There is a tendency to underestimate the heights of low waves, and overestimate the heights of high ones. There are numerous accounts of waves 75 to 80 feet high, or even higher, although waves more than 55 feet high are very rare. Wavelength is usually underestimated. The motions of the vessel from which measurements are made contribute to such errors.

Height. Measurement of wave height is particularly difficult. A microbarograph can be used if the wave is long enough or the vessel small enough to permit the vessel to ride from crest to trough. If the waves are approaching from dead ahead or dead astern, this requires a wavelength at least twice the length of the vessel. For most accurate results the instrument should be placed at the center of roll and pitch, to minimize the effects of these motions. Wave height can often be estimated with reasonable accuracy by comparing it with freeboard of the vessel. This is less accurate as wave height and vessel motion increase. If a point of observation can be found at which the top of a wave is in line with the horizon when the observer is in the trough, the wave height is equal to height of eye. However, if the vessel is rolling or pitching, this height at the moment of observation may be difficult to determine. The highest wave ever reliably reported was 112 feet observed from the USS Ramapo in 1933.

Length. The dimensions of the vessel can be used to determine wavelength. Errors are introduced by perspective and disturbance of the wave pattern by the vessel. These errors are minimized if observations are made from maximum height. Best results are obtained if the sea is from dead ahead or dead astern.

Period. If allowance is made for the motion of the vessel, wave period can be determined by measuring the interval between passages of wave crests past the observer. The relative motion of the vessel can be eliminated by timing the passage of successive wave crests past a patch of foam or a floating object at some distance from the vessel. Accuracy of results can be improved by averaging several observations.

Speed. Speed can be determined by timing the passage of the wave between measured points along the side of the ship, if corrections are applied for the direction of travel for the wave and the speed of the ship.

The length, period, and speed of waves are interrelated by the relationships indicated previously. There is no definite mathematical relationship between wave height and length, period, or speed.

3309. Tsunamis

Tsunamis are ocean waves produced by sudden, large-scale motion of a portion of the ocean floor or the shore, such as a volcanic eruption, earthquake (sometimes called seaquake if it occurs at sea), or landslide. If they are caused by a submarine earthquake, they are usually called **seismic sea waves**. The point directly above the disturbance, at which the waves originate, is called the **epicenter**. Either a tsunami or a storm tide that overflows the land is popularly called a **tidal wave**, although it bears no relation to the tide.

If a volcanic eruption occurs below the surface of the sea, the escaping gases cause a quantity of water to be pushed upward in the shape of a dome. The same effect is caused by the sudden rising of a portion of the bottom. As this water settles back, it creates a wave which travels at high speed across the surface of the ocean.

Tsunamis are a series of waves. Near the epicenter, the first wave may be the highest. At greater distances, the highest wave usually occurs later in the series, commonly between the third and the eighth wave. Following the maximum, they again become smaller, but the tsunami may be detectable for several days.

In deep water the wave height of a tsunami is probably never greater than 2 or 3 feet. Since the wavelength is usually considerably more than 100 miles, the wave is not conspicuous at sea. In the Pacific, where most tsunamis occur, the wave period varies between about 15 and 60 minutes, and the speed in deep water is more than 400 knots. The approximate speed can be computed by the formula:

$$S = 0.6\sqrt{gd} = 3.4\sqrt{d}\Delta\delta\gamma\Gamma$$

where S is the speed in knots, g is the acceleration due to gravity (32.2 feet per second per second), and d is the depth of water in feet. This formula is applicable to any wave in water having a depth of less than half the wavelength. For most ocean waves it applies only in shallow water, because of the relatively short wavelength.

When a tsunami enters shoal water, it undergoes the same changes as other waves. The formula indicates that speed is proportional to depth of water. Because of the great speed of a tsunami when it is in relatively deep water, the slowing is relatively much greater than that of an ordinary wave crested by wind. Therefore, the increase in height is also much greater. The size of the wave depends upon the nature and intensity of the disturbance. The height and destructiveness of the wave arriving at any place depends upon its distance from the epicenter, topography of the ocean floor, and the coastline. The angle at which the wave arrives, the shape of the coastline, and the topography along the coast and offshore, all have an effect. The position of the shore is also a factor, as it may be sheltered by intervening land, or be in a position where waves have a tendency to converge, either because of refraction or reflection, or both.

Tsunamis 50 feet in height or higher have reached the shore, inflicting widespread damage. On April 1, 1946, seismic sea waves originating at an epicenter near the Aleutians, spread over the entire Pacific. Scotch Cap Light on Unimak Island, 57 feet above sea level, was completely destroyed. Traveling at an average speed of 490 miles per hour, the waves reached the Hawaiian Islands in 4 hours and 34 minutes, where they arrived as waves 50 feet above the high water level, and flooded a strip of coast more than 1,000 feet wide at some places. They left a death toll of 173 and property damage of $25 million. Less destructive waves reached the shores of North and South America, as well as Australia, 6,700 miles from the epicenter.

After this disaster, a tsunami warning system was set up in the Pacific, even though destructive waves are relatively rare (averaging about one in 20 years in the Hawaiian Islands). This system monitors seismic disturbances throughout the Pacific basin and predicts times and heights of tsunamis. Warnings are immediately sent out if a disturbance is detected.

In addition to seismic sea waves, earthquakes below the surface of the sea may produce a longitudinal wave that travels upward at the speed of sound. When a ship encounters such a wave, it is felt as a sudden shock which may be so severe that the crew thinks the vessel has struck bottom.

3310. Storm Tides

In relatively tideless seas like the Baltic and Mediterranean, winds cause the chief fluctuations in sea level. Elsewhere, the astronomical tide usually masks these variations. However, under exceptional conditions, either severe extra-tropical storms or tropical cyclones can produce changes in sea level that exceed the normal range of tide. Low sea level is of little concern except to shipping, but a rise above ordinary high-water mark, particularly when it is accompanied by high waves, can result in a catastrophe.

Although, like tsunamis, these storm tides or storm

surges are popularly called tidal waves, they are not associated with the tide. They consist of a single wave crest and hence have no period or wavelength.

Three effects in a storm induce a rise in sea level. The first is wind stress on the sea surface, which results in a piling-up of water (sometimes called "wind set-up"). The second effect is the convergence of wind-driven currents, which elevates the sea surface along the convergence line. In shallow water, bottom friction and the effects of local topography cause this elevation to persist and may even intensify it. The low atmospheric pressure that accompanies severe storms causes the third effect, which is sometimes referred to as the "inverted barometer." An inch of mercury is equivalent to about 13.6 inches of water, and the adjustment of the sea surface to the reduced pressure can amount to several feet at equilibrium.

All three of these causes act independently, and if they happen to occur simultaneously, their effects are additive. In addition, the wave can be intensified or amplified by the effects of local topography. Storm tides may reach heights of 20 feet or more, and it is estimated that they cause three-fourths of the deaths attributed to hurricanes.

3311. Standing Waves And Seiches

Previous articles in this chapter have dealt with progressive waves which appear to move regularly with time. When two systems of progressive waves having the same period travel in opposite directions across the same area, a series of **standing waves** may form. These appear to remain stationary.

Another type of standing wave, called a **seiche**, sometimes occurs in a confined body of water. It is a long wave, usually having its crest at one end of the confined space, and its trough at the other. Its period may be anything from a few minutes to an hour or more, but somewhat less than the tidal period. Seiches are usually attributed to strong winds or differences in atmospheric pressure.

3312. Tide Waves

There are, in general, two regions of high tide separated by two regions of low tide, and these regions move progressively westward around the earth as the moon revolves in its orbit. The high tides are the crests of these tide waves, and the low tides are the troughs. The wave is not noticeable at sea, but becomes apparent along the coasts, particularly in funnel-shaped estuaries. In certain river mouths, or estuaries of particular configuration, the incoming wave of high water overtakes the preceding low tide, resulting in a high-crested, roaring wave which progresses upstream in a surge called a **bore**.

3313. Internal Waves

Thus far, the discussion has been confined to waves on the surface of the sea, the boundary between air and water. Internal waves, or boundary waves, are created below the surface, at the boundaries between water strata of different densities. The density differences between adjacent water strata in the sea are considerably less than that between sea and air. Consequently, internal waves are much more easily formed than surface waves, and they are often much larger. The maximum height of wind waves on the surface is about 60 feet, but internal wave heights as great as 300 feet have been encountered.

Internal waves are detected by a number of observations of the vertical temperature distribution, using recording devices such as the bathythermograph. They have periods as short as a few minutes, and as long as 12 or 24 hours, these greater periods being associated with the tides.

A slow-moving ship, operating in a freshwater layer having a depth approximating the draft of the vessel, may produce short-period internal waves. This may occur off rivers emptying into the sea, or in polar regions in the vicinity of melting ice. Under suitable conditions, the normal propulsion energy of the ship is expended in generating and maintaining these internal waves and the ship appears to "stick" in the water, becoming sluggish and making little headway. The phenomenon, known as **dead water**, disappears when speed is increased by a few knots.

The full significance of internal waves has not yet been determined, but it is known that they may cause submarines to rise and fall like a ship at the surface, and they may also affect sound transmission in the sea.

3314. Waves And Ships

The effects of waves on a ship vary considerably with the type of ship, its course and speed, and the condition of the sea. A short vessel has a tendency to ride up one side of a wave and down the other side, while a larger vessel may tend to ride through the waves on an even keel. If the waves are of such length that the bow and stern of a vessel are alternately riding in successive crests and troughs, the vessel is subject to heavy sagging and hogging stresses, and under extreme conditions may break in two. A change of heading may reduce the danger. Because of the danger from sagging and hogging, a small vessel is sometimes better able to ride out a storm than a large one.

If successive waves strike the side of a vessel at the same phase of successive rolls, relatively small waves can cause heavy rolling. The same effect, if applied to the bow or stern in time with the natural period of pitch, can cause heavy pitching. A change of either heading or speed can quickly reduce the effect.

A wave having a length twice that of a ship places that ship in danger of falling off into the trough of the sea, particularly if it is a slow-moving vessel. The effect is especially pronounced if the sea is broad on the bow or broad on the quarter. An increase of speed reduces the hazard.

3315. Using Oil To Calm Breaking Waves

Historically oil was effective in modifying the effects of breaking waves, and was useful to vessels when lowering or hoisting boats in rough weather. Its effect was greatest in

deep water, where a small quantity sufficed if the oil were made to spread to windward of the vessel.

Environmental concerns have led to this procedure being discontinued.

BREAKERS AND SURF

3316. Refraction

As explained previously, waves are slowed in shallow water, causing refraction if the waves approach the beach at an angle. Along a perfectly straight beach, with uniform shoaling, the wave fronts tend to become parallel to the shore. Any irregularities in the coastline or bottom contours, however, affect the refraction, causing irregularities. In the case of a ridge perpendicular to the beach, for instance, the shoaling is more rapid, causing greater refraction towards the ridge. The waves tend to align themselves with the bottom contours. Waves on both sides of the ridge have a component of motion toward the ridge. This convergence of wave energy toward the ridge causes an increase in wave or breaker height. A submarine canyon or valley perpendicular to the beach, on the other hand, produces divergence, with a decrease in wave or breaker height. These effects are illustrated in Figure 3316. Bends in the coast line have a similar effect, convergence occurring at a point, and divergence if the coast is concave to the sea. Points act as focal areas for wave energy and experience large breakers. Concave bays have small breakers because the energy is spread out as the waves approach the beach.

Under suitable conditions, currents also cause refraction. This is of particular importance at entrances of tidal estuaries. When waves encounter a current running in the opposite direction, they become higher and shorter. This results in a choppy sea, often with breakers. When waves move in the same direction as current, they decrease in height, and become longer. Refraction occurs when waves encounter a current at an angle.

Refraction diagrams, useful in planning amphibious operations, can be prepared with the aid of nautical charts or aerial photographs. When computer facilities are available, computer programs can be used to produce refraction diagrams quickly and accurately.

3317. Classes Of Breakers

In deep water, swell generally moves across the surface as somewhat regular, smooth undulations. When shoal water is reached, the wave period remains the same, but the speed decreases. The amount of decrease is negligible until the depth of water becomes about one-half the wavelength, when the waves begin to “feel” bottom. There is a slight decrease in wave height, followed by a rapid increase, if the waves are traveling perpendicular to a straight coast with a uniformly sloping bottom. As the waves become higher and

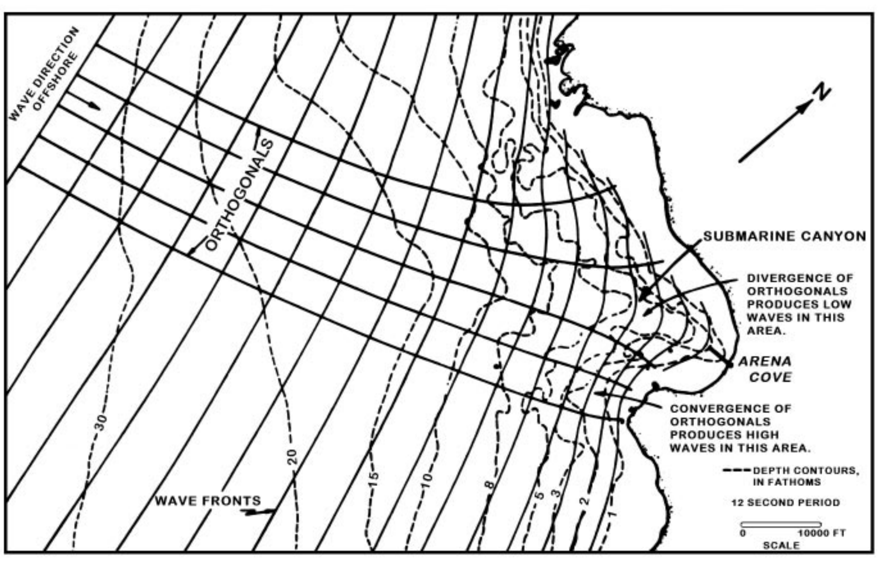


Figure 3316. The effect of bottom topography in causing wave convergence and wave divergence.
Courtesy of Robert L. Wiegel, Council on Wave Research, University of Californiia.

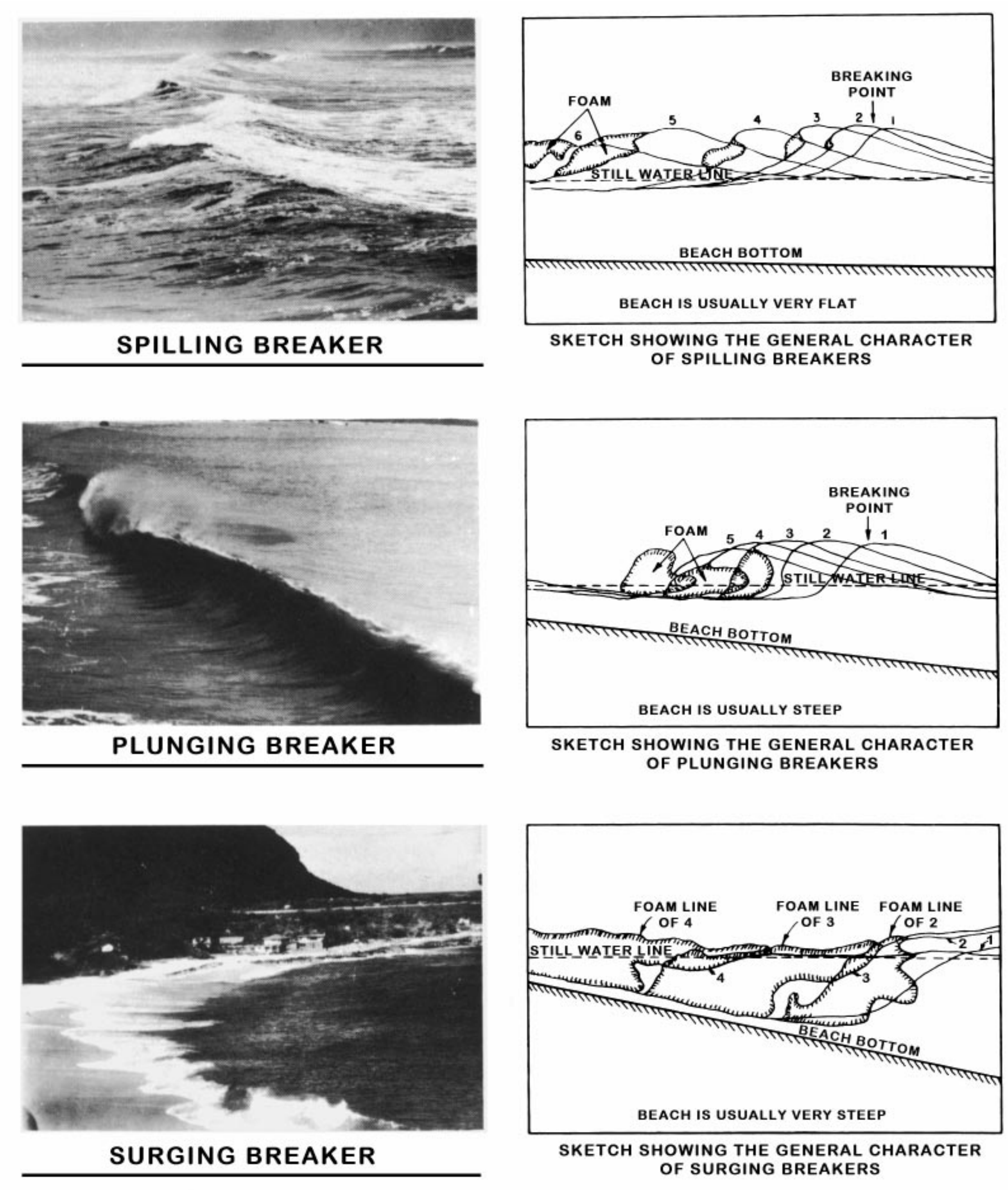


Figure 3317. The three types of breakers.
Courtesy of Robert L. Wiegel, Council on Wave Research, University of California.

shorter, they also become steeper, and the crest narrows. When the speed of the crest becomes greater than that of the wave, the front face of the wave becomes steeper than the rear face. This process continues at an accelerating rate as the depth of water decreases. If the wave becomes too unstable, it topples forward to form a breaker.

There are three general classes of breakers. A **spilling breaker** breaks gradually over a considerable distance. A **plunging breaker** tends to curl over and break with a single crash. A **surging breaker** peaks up, but surges up the beach without spilling or plunging. It is classed as a breaker even though it does not actually break. The type of breaker which forms is determined by the steepness of the beach and the steepness of the wave before it reaches shallow water, as illustrated in Figure 3317.

Long waves break in deeper water, and have a greater breaker height. A steep beach also increases breaker height. The height of breakers is less if the waves approach the beach at an acute angle. With a steeper beach slope there is greater tendency of the breakers to plunge or surge. Following the uprush of water onto a beach after the breaking of a wave, the seaward backrush occurs. The returning water is called **backwash**. It tends to further slow the bottom of a wave, thus increasing its tendency to break. This effect is

greater as either the speed or depth of the backwash increases. The still water depth at the point of breaking is approximately 1.3 times the average breaker height.

Surf varies with both position along the beach and time. A change in position often means a change in bottom contour, with the refraction effects discussed before. At the same point, the height and period of waves vary considerably from wave to wave. A group of high waves is usually followed by several lower ones. Therefore, passage through surf can usually be made most easily immediately following a series of higher waves.

Since surf conditions are directly related to height of the waves approaching a beach, and to the configuration of the bottom, the state of the surf at any time can be predicted if one has the necessary information and knowledge of the principles involved. Height of the sea and swell can be predicted from wind data, and information on bottom configuration can sometimes be obtained from the largest scale nautical chart. In addition, the area of lightest surf along a beach can be predicted if details of the bottom configuration are available. Surf predictions may, however, be significantly in error due to the presence of swell from unknown storms hundreds of miles away.

3318. Currents In The Surf Zone

In and adjacent to the surf zone, currents are generated by waves approaching the bottom contours at an angle, and by irregularities in the bottom.

Waves approaching at an angle produce a **longshore current** parallel to the beach, inside of the surf zone. Longshore currents are most common along straight beaches. Their speeds increase with increasing breaker height, decreasing wave period, increasing angle of breaker line with the beach, and increasing beach slope. Speed seldom exceeds 1 knot, but sustained speeds as high as 3 knots have been recorded. Longshore currents are usually constant in direction. They increase the danger of landing craft broaching to.

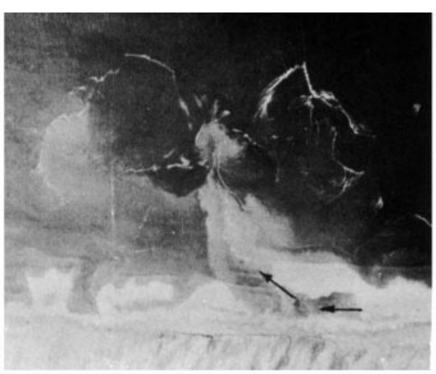
Where the bottom is sandy a good distance offshore, one or more **sand bars** typically form. The innermost bar will break in even small waves, and will isolate the longshore current. The second bar, if one forms, will break only in heavier weather, and the third, if present, only in storms. It is possible to move parallel to the coast in small craft in relatively deep water in the area between these bars, between the lines of breakers.

3319. Rip Currents

As explained previously, wave fronts advancing over nonparallel bottom contours are refracted to cause convergence or divergence of the energy of the waves. Energy concentrations in areas of convergence form barriers to the returning backwash, which is deflected along the beach to areas of less resistance. Backwash accumulates at weak points, and returns seaward in concentrations, forming **rip currents** through the surf. At these points the large volume of returning water has a retarding effect upon the incoming waves, thus adding to the condition causing the rip current. The waves on one or both sides of the rip, having greater energy and not being retarded by the concentration of backwash, advance faster and farther up the beach. From here, they move along the beach as feeder currents. At some point of low resistance, the water flows seaward through the surf, forming the neck of the rip current. Outside the breaker line the current widens and slackens, forming the head. The various parts of a rip current are shown in Figure 3319.

Rip currents may also be caused by irregularities in the beach face. If a beach indentation causes an uprush to advance farther than the average, the backrush is delayed and this in turn retards the next incoming foam line (the front of a wave as it advances shoreward after breaking) at that point. The foam line on each side of the retarded point continues in its advance, however, and tends to fill in the retarded area, producing a rip current.

Rip currents are dangerous for swimmers, but may provide a clear path to the beach for small craft, as they tend to scour out the bottom and break through any sand bars that



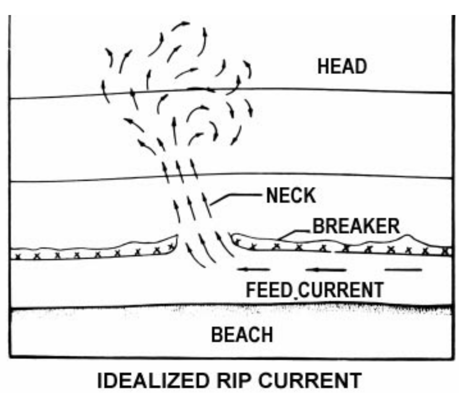


Figure 3319. A rip current (left) and a diagram of its parts (right).
Courtesy of Robert L. Wiegel, Council on Wave Research, University of California.

have formed. Rip currents also change location over time as conditions change.

3320. Beach Sediments

In the surf zone, large amounts of sediment are suspended in the water. When the water's motion decreases, the sediments settle to the bottom. The water motion can be either waves or currents. Promontories or points are rocky because the large breakers scour the points and small sediments are suspended in the water and carried away. Bays tend to have sandy beaches because of the smaller waves.

In the winter when storms create large breakers and surf, the waves erode beaches and carry the particles offshore where offshore sand bars form; sandy beaches tend to be narrower in stormy seasons. In the summer the waves gradually move the sand back to the beaches and the offshore sand bars decrease; then sandy beaches tend to be wider.

Longshore currents move large amounts of sand along the coast. These currents deposit sand on the upcurrent side of a jetty or pier, and erode the beach on the downcurrent side. Groins are sometime built to impede the longshore flow of sediments and preserve beaches for recreational use. As with jetties, the downcurrent side of each groin will have the best water for approaching the beach.

CHAPTER 34

ICE IN THE SEA

INTRODUCTION

3400. Ice And The Navigator

Sea ice has posed a problem to the polar navigator since antiquity. During a voyage from the Mediterranean to England and Norway sometime between 350 BC and 300 BC, Pytheas of Massalia sighted a strange substance which he described as “neither land nor air nor water” floating upon and covering the northern sea over which the summer sun barely set. Pytheas named this lonely region Thule, hence Ultima Thule (farthest north or land’s end). Thus began over 20 centuries of polar exploration.

Ice is of direct concern to the navigator because it restricts and sometimes controls his movements; it affects his dead reckoning by forcing frequent and sometimes inaccurately determined changes of course and speed; it affects his piloting by altering the appearance or obliterating the features of landmarks; it hinders the establishment and maintenance of aids to navigation; it affects his use of electronics by affecting propagation of radio waves; it produces changes in surface features and in radar returns from these features; it affects celestial navigation by altering the refraction and obscuring the horizon and celestial bodies either directly or by the weather it influences, and it affects charts by introducing several plotting problems.

Because of his direct concern with ice, the prospective polar navigator must acquaint himself with its nature and extent in the area he expects to navigate. In addition to this volume, books, articles, and reports of previous polar operations and expeditions will help acquaint the polar navigator with the unique conditions at the ends of the earth.

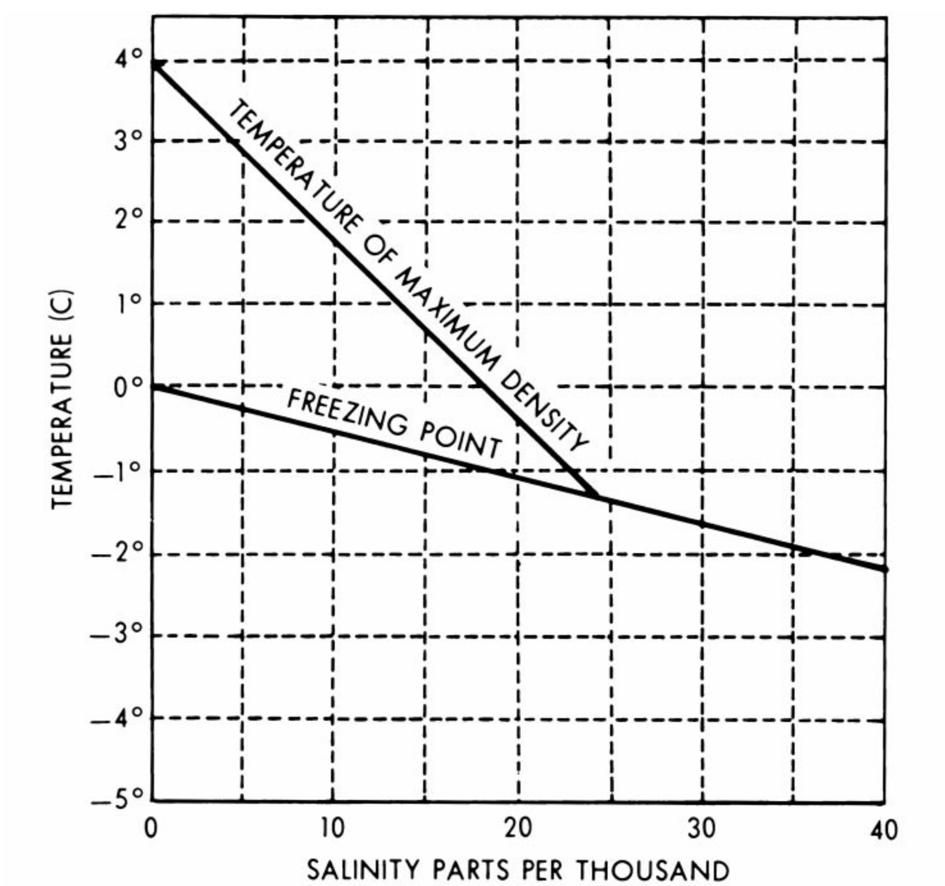


Figure 3401. Relationship between temperature of maximum density and freezing point for water of varying salinity.

3401. Formation Of Ice

As it cools, water contracts until the temperature of maximum density is reached. Further cooling results in expansion. The maximum density of fresh water occurs at a temperature of 4.0°C, and freezing takes place at 0°C. The addition of salt lowers both the temperature of maximum density and, to a lesser extent, that of freezing. These relationships are shown in Figure 3401. The two lines meet at a salinity of 24.7 parts per thousand, at which maximum density occurs at the freezing temperature of –1.3°C. At this and greater salinities, the temperature of maximum density of sea water is coincident with the freezing point temperature, i. e., the density increases as the temperature gets colder. At a salinity of 35 parts per thousand, the approximate average for the oceans, the freezing point is –1.88°C.

As the density of surface seawater increases with decreasing temperature, convective density-driven currents are induced bringing warmer, less dense water to the surface. If the polar seas consisted of water with constant salinity, the entire water column would have to be cooled to the freezing point in this manner before ice would begin to form. This is not the case, however, in the polar regions where the vertical salinity distribution is such that the surface waters are underlain at shallow depth by waters of higher salinity. In this instance density currents form a shallow mixed layer which subsequently cannot mix with the deep layer of warmer but saltier water. Ice will then begin forming at the water surface when density currents cease and the surface water reaches its freezing point. In shoal water, however, the mixing process can be sufficient to extend the freezing temperature from the surface to the bottom. Ice crystals can, therefore, form at any depth in this case. Because of their decreased density, they tend to rise to the surface, unless they form at the bottom and attach themselves there. This ice, called anchor ice, may continue to grow as additional ice freezes to that already formed.

3402. Land Ice

Ice of land origin is formed on land by the freezing of freshwater or the compacting of snow as layer upon layer adds to the pressure on that beneath.

Under great pressure, ice becomes slightly plastic, and is forced downward along an inclined surface. If a large area is relatively flat, as on the Antarctic plateau, or if the outward flow is obstructed, as on Greenland, an **ice cap** forms and remains throughout the year. The thickness of these ice caps ranges from nearly 1 kilometer on Greenland to as much as 4.5 kilometers on the Antarctic Continent. Where ravines or mountain passes permit flow of the ice, a **glacier** is formed. This is a mass of snow and ice which continuously flows to lower levels, exhibiting many of the characteristics of rivers of water. The flow may be more than 30 meters per day, but is generally much less. When a glacier reaches a comparatively level area, it spreads out. When a glacier flows into the sea, the buoyant force of the water breaks off pieces from time to time, and these float away as **icebergs**. Icebergs may be described as dome shaped, sloping or pinnacled (Figure 3402a), tabular (Figure 3402b), glacier, or weathered.

A floating iceberg seldom melts uniformly because of lack of uniformity in the ice itself, differences in the temperature above and below the waterline, exposure of one side to the sun, strains, cracks, mechanical erosion, etc. The inclusion of rocks, silt, and other foreign matter further accentuates the differences. As a result, changes in equilibrium take place, which may cause the berg to periodically tilt or capsize. Parts of it may break off or **calve**, forming separate smaller bergs. A relatively large piece of floating ice, generally extending 1 to 5 meters above the sea surface and normally about 100 to 300 square meters in area, is called a **bergy bit**. A smaller piece of ice large enough to inflict serious damage to a vessel is called a **growler** because of the noise it sometimes makes as it bobs up and down in the sea. Growlers extend less than 1 meter above the sea surface and normally occupy an area of about 20 square meters. Bergy bits and growlers are usually pieces calved from icebergs, but they may be the remains of a mostly melted iceberg.

The principal danger from icebergs is their tendency to break or capsize. Soon after a berg is calved, while remaining in far northern waters, 60–80% of its bulk is submerged. But as the berg drifts into warmer waters, the underside can sometimes melt faster than the exposed portion, especially in very cold weather. As the mass of the submerged portion deteriorates, the berg becomes increasingly unstable, and it will eventually roll over. Icebergs that have not yet capsized have a jagged and possibly dirty appearance. A recently capsized berg will be smooth, clean, and curved in appearance. Previous waterlines at odd angles can sometimes be seen after one or more capsizings.

The stability of a berg can sometimes be noted by its reaction to ocean swells. The livelier the berg, the more unstable it is. It is extremely dangerous for a vessel to approach an iceberg closely, even one which appears stable, because in addition to the danger from capsizing, unseen cracks can cause icebergs to split in two or calve off large chunks.

Another danger is from underwater extensions, called **rams**, which are usually formed due to melting or erosion above the waterline at a faster rate than below. Rams may also extend from a vertical ice cliff, also known as an **ice front**, which forms the seaward face of a massive ice sheet or floating glacier; or from an **ice wall**, which is the ice cliff forming the seaward margin of a glacier which is aground. In addition to rams, large portions of an iceberg may extend well beyond the waterline at greater depths.

Strangely, icebergs may be helpful to the mariner in some ways. The melt water found on the surface of icebergs is a source of freshwater, and in the past some daring seamen have made their vessels fast to icebergs which, because they are affected more by currents than the wind, have proceeded to tow them out of the ice pack.

Icebergs can be used as a navigational aid in extreme latitudes where charted depths may be in doubt or non-existent. Since an iceberg (except a large tabular berg) must be at least as deep in the water as it is high to remain upright, a grounded berg can provide an estimate of the minimum water depth at its location. Water depth will be at least equal to the exposed height of the grounded iceberg. Grounded bergs remain stationary while current and wind move sea ice past them. Drifting ice may pile up against the upcurrent side of a grounded berg.

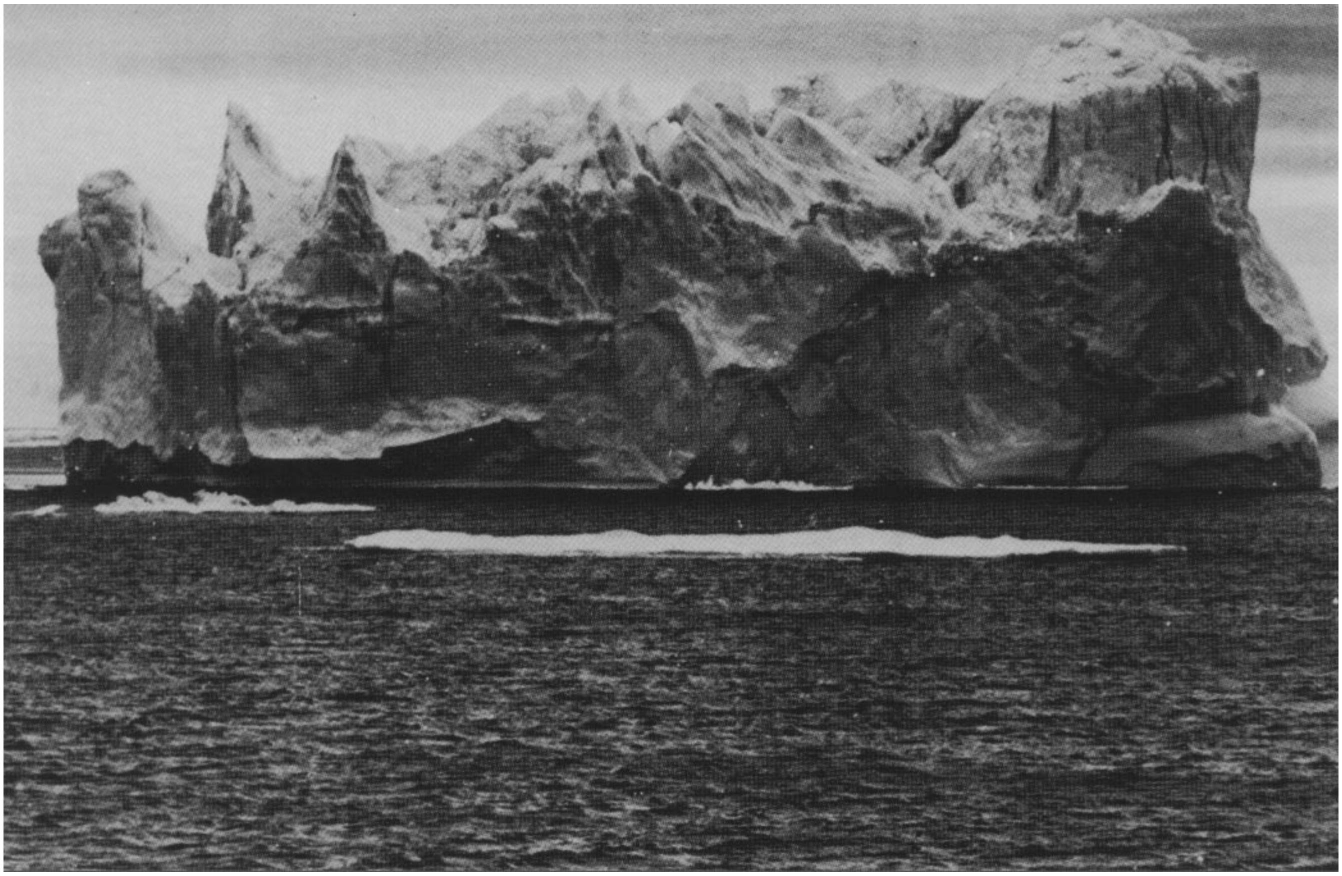


Figure 3402a. Pinnacled iceberg.

Figure 3402b. A tabular iceberg.

3403. Sea Ice

Sea ice forms by the freezing of seawater and accounts for 95 percent of all ice encountered. The first indication of the formation of new sea ice (up to 10 centimeters in thickness) is the development of small individual, needle-like crystals of ice, called **spicules**, which become suspended in the top few centimeters of seawater. These spicules, also known as **frazil ice**, give the sea surface an oily appearance. **Grease ice** is formed when the spicules coagulate to form a soupy layer on the surface, giving the sea a matte appearance. The next stage in sea ice formation occurs when **shuga**, an accumulation of spongy white ice lumps a few centimeters across, develops from grease ice. Upon further freezing, and depending upon wind exposure, seas, and salinity, shuga and grease ice develop into **nilas**, an elastic crust of high salinity, up to 10 centimeters in thickness, with a matte surface, or into **ice rind**, a brittle, shiny crust of low salinity with a thickness up to approximately 5 centimeters. A layer of 5 centimeters of freshwater ice is brittle but strong enough to support the weight of a heavy man. In contrast, the same thickness of newly formed sea ice will support not more than about 10 percent of this weight, although its strength varies with the temperatures at which it is formed; very cold ice supports a greater weight than warmer ice. As it ages, sea ice becomes harder and more brittle.

New ice may also develop from slush which is formed when snow falls into seawater which is near its freezing point, but colder than the melting point of snow. The snow does not melt, but floats on the surface, drifting with the wind into beds. If the temperature then drops below the freezing point of the seawater, the slush freezes quickly into a soft ice similar to shuga.

Sea ice is exposed to several forces, including currents, waves, tides, wind, and temperature variations. In its early stages, its plasticity permits it to conform readily to virtually any shape required by the forces acting upon it. As it becomes older, thicker, more brittle, and exposed to the influence of wind and wave action, new ice usually separates into circular pieces from 30 centimeters to 3 meters in diameter and up to approximately 10 centimeters in thickness with raised edges due to individual pieces striking against each other. These circular pieces of ice are called **pancake ice** (Figure 3403) and may break into smaller pieces with strong wave motion. Any single piece of relatively flat sea ice less than 20 meters across is called an **ice cake**. With continued low temperatures, individual ice cakes and pancake ice will, depending on wind or wave motion, either freeze together to form a continuous sheet or unite into pieces of ice 20 meters or more across. These larger pieces are then called **ice floes**, which may further freeze together to form an ice covered area greater than 10 kilometers across known as an **ice field**. In wind sheltered areas thickening ice usually forms a continuous sheet before it can develop into the characteristic ice cake form. When sea ice reaches a thickness of between 10 to 30 centimeters it is referred to as **gray** and **gray-white ice**, or collectively as **young ice**, and

Figure 3403. Pancake ice, with an iceberg in the background.

is the transition stage between nilas and first-year ice. First-year ice usually attains a thickness of between 30 centimeters and 2 meters in its first winter's growth.

Sea ice may grow to a thickness of 10 to 13 centimeters within 48 hours, after which it acts as an insulator between the ocean and the atmosphere progressively slowing its further growth. However, sea ice may grow to a thickness of between 2 to 3 meters in its first winter. Ice which has survived at least one summer's melt is classified as **old ice**. If it has survived only one summer's melt it may be referred to as **second-year ice**, but this term is seldom used today. Old ice which has attained a thickness of 3 meters or more and has survived at least two summers' melt is known as **multiyear ice** and is almost salt free. This term is increasingly used to refer to any ice more than one season old. Old ice can be recognized by a bluish tone to its surface color in contrast to the greenish tint of first-year ice, but it is often covered with snow. Another sign of old ice is a smoother, more rounded appearance due to melting/refreezing and weathering.

Greater thicknesses in both first and multiyear ice are attained through the deformation of the ice resulting from the movement and interaction of individual floes. Deformation processes occur after the development of new and young ice and are the direct consequence of the effects of winds, tides, and currents. These processes transform a relatively flat sheet of ice into pressure ice which has a rough surface. **Bending**, which is the first stage in the formation of pressure ice, is the upward or downward motion of thin and very plastic ice. Rarely, **tenting** occurs when bending produces an upward displacement of ice forming a flat sided arch with a cavity beneath. More frequently, however, **rafting** takes place as one piece of ice overrides another. When pieces of first-year ice are piled haphazardly over one another forming a wall or line of broken ice, referred to as a **ridge**, the process is known as **ridging**. Pressure ice with topography consisting of numerous mounds or hillocks is called

hummocked ice, each mound being called a **hummock**.

The motion of adjacent floes is seldom equal. The rougher the surface, the greater is the effect of wind, since each piece extending above the surface acts as a sail. Some ice floes are in rotary motion as they tend to trim themselves into the wind. Since ridges extend below as well as above the surface, the deeper ones are influenced more by deep water currents. When a strong wind blows in the same direction for a considerable period, each floe exerts pressure on the next one, and as the distance increases, the pressure becomes tremendous. Ridges on sea ice are generally about 1 meter high and 5 meters deep, but under considerable pressure may attain heights of 20 meters and depths of 50 meters in extreme cases.

The alternate melting and growth of sea ice, combined with the continual motion of various floes that results in separation as well as consolidation, causes widely varying conditions within the ice cover itself. The mean areal density, or concentration, of pack ice in any given area is expressed in tenths. Concentrations range from: open water (total concentration of all ice is less than one tenth), very open pack (1 to 3 tenths concentration), open pack (4 to 6 tenths concentration), close pack (7 to 8 tenths concentration), very close pack (9 to 10 to less than 10 to 10 concentration), to compact or consolidated pack (10 to 10 or complete coverage). The extent to which an ice cover of varying concentrations can be penetrated by a vessel varies from place to place and with changing weather conditions. With a concentration of 1 to 3 tenths in a given area, an unreinforced vessel can generally navigate safely, but the danger of receiving heavy damage is always present. When the concentration increases to between 3 and 5 tenths, the area becomes only occasionally accessible to an unreinforced vessel, depending upon the wind and current. With concentrations of 5 to 7 tenths, the area becomes accessible only to ice strengthened vessels, which on occasion will require icebreaker assistance. Navigation in areas with concentrations of 7 tenths or more should only be attempted by icebreakers.

Within the ice cover, openings may develop resulting from a number of deformation processes. Long, jagged **cracks** may appear first in the ice cover or through a single floe. When these cracks part and reach lengths of a few meters to many kilometers, they are referred to as **fractures**. If they widen further to permit passage of a ship, they are called **leads**. In winter, a thin coating of new ice may cover the water within a lead, but in summer the water usually remains ice-free until a shift in the movement forces the two sides together again. A lead ending in a pressure ridge or other impenetrable barrier is a **blind lead**.

A lead between pack ice and shore is a **shore lead**, and one between pack and fast ice is a **flaw lead**. Navigation in these two types of leads is dangerous, because if the pack ice closes with the fast ice, the ship can be caught between the two, and driven aground or caught in the shear zone between.

Before a lead refreezes, lateral motion generally occurs between the floes, so that they no longer fit and unless the pressure is extreme, numerous large patches of open water remain. These nonlinear shaped openings enclosed in ice are called **polynyas**. Polynyas may contain small fragments of floating ice and may be covered with miles of new and young ice. **Recurring polynyas** occur in areas where upwelling of relatively warmer water occurs periodically. These areas are often the site of historical native settlements, where the polynyas permit fishing and hunting at times before regular seasonal ice breakup. Thule, Greenland, is an example.

Sea ice which is formed *in situ* from seawater or by the freezing of pack ice of any age to the shore and which remains attached to the coast, to an ice wall, to an ice front, or between shoals is called **fast ice**. The width of this fast ice varies considerably and may extend for a few meters or several hundred kilometers. In bays and other sheltered areas, fast ice, often augmented by annual snow accumulations and the seaward extension of land ice, may attain a thickness of over 2 meters above the sea surface. When a floating sheet of ice grows to this or a greater thickness and extends over a great horizontal distance, it is called an **ice shelf**. Massive ice shelves, where the ice thickness reaches several hundred meters, are found in both the Arctic and Antarctic.

The majority of the icebergs found in the Antarctic do not originate from glaciers, as do those found in the Arctic, but are calved from the outer edges of broad expanses of shelf ice. Icebergs formed in this manner are called **tabular icebergs**, having a box like shape with horizontal dimensions measured in kilometers, and heights above the sea surface approaching 60 meters. See Figure 3402b. The largest Antarctic ice shelves are found in the Ross and Weddell Seas. The expression “tabular iceberg” is not applied to bergs which break off from Arctic ice shelves; similar formations there are called **ice islands**. These originate when shelf ice, such as that found on the northern coast of Greenland and in the bays of Ellesmere Island, breaks up. As a rule, Arctic ice islands are not as large as the tabular icebergs found in the Antarctic. They attain a thickness of up to 55 meters and on the average extend 5 to 7 meters above the sea surface. Both tabular icebergs and ice islands possess a gently rolling surface. Because of their deep draft, they are influenced much more by current than wind. Arctic ice islands have been used as floating scientific platforms from which polar research has been conducted.

3404. Thickness Of Sea Ice

Sea ice has been observed to grow to a thickness of almost 3 meters during its first year. However, the thickness of first-year ice that has not undergone deformation does not generally exceed 2 meters. In coastal areas where the melting rate is less than the freezing rate, the thickness may increase during succeeding winters, being augmented by compacted and frozen snow, until a maximum thickness of about 3.5 to 4.5 meters may eventually be reached. Old sea ice may also attain a thickness of over 4 meters in this manner, or when summer melt water from its surface or from snow cover runs off into the sea and refreezes under the ice where the seawater temperature is

below the freezing point of the fresher melt water.

The growth of sea ice is dependent upon a number of meteorological and oceanographic parameters. Such parameters include air temperature, initial ice thickness, snow depth, wind speed, seawater salinity and density, and the specific heats of sea ice and seawater. Investigations, however, have shown that the most influential parameters affecting sea ice growth are air temperature, wind speed, snow depth and initial ice thickness. Many complex equations have been formulated to predict ice growth using these four parameters. However, except for the first two, these parameters are not routinely observed for remote polar locations.

Field measurements suggest that reasonable growth estimates can be obtained from air temperature data alone.Various empirical formulae have been developed based on this premise. All appear to perform better under thin

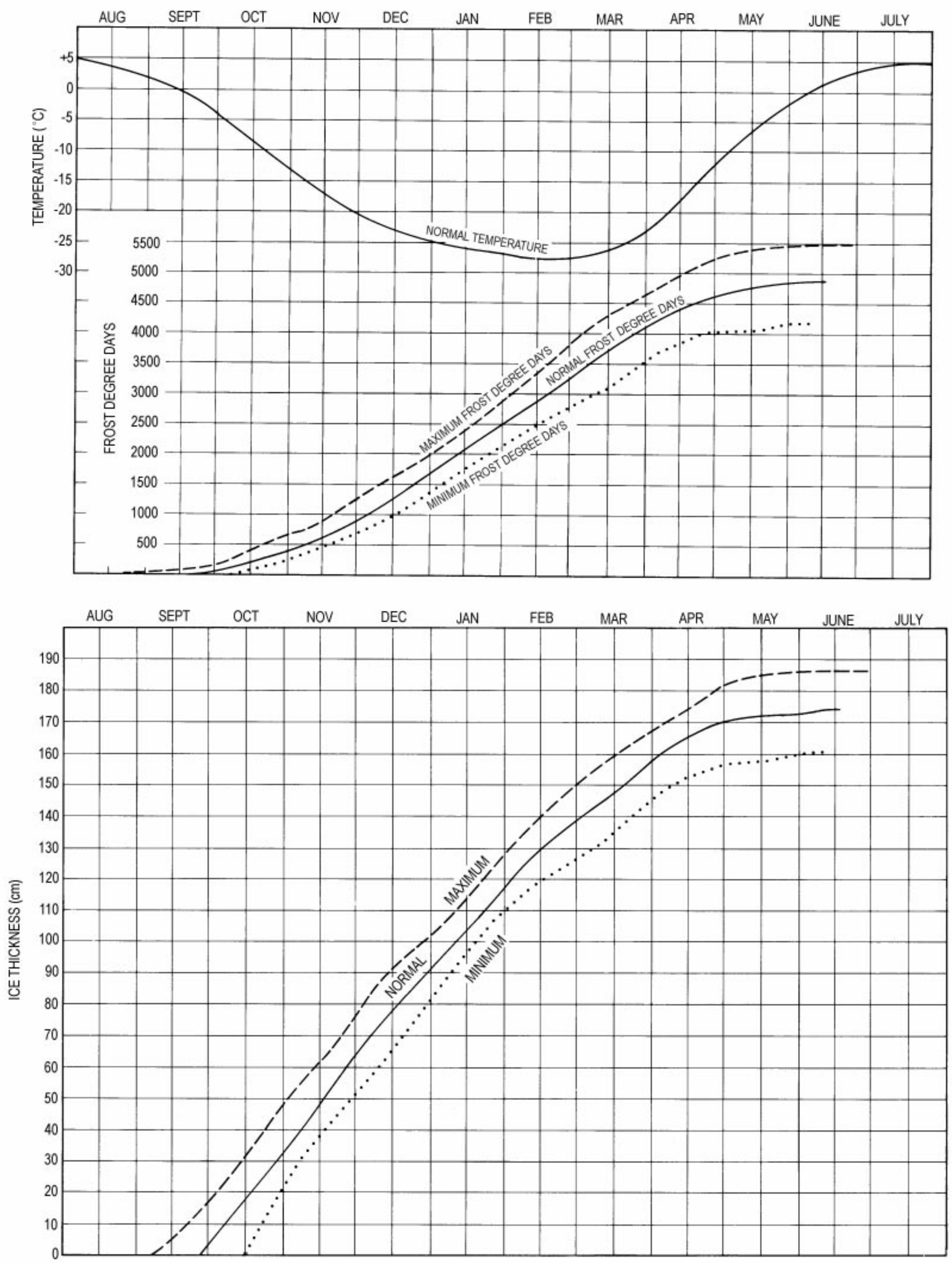


Figure 3404a. Relationship between accumulated frost degree days and theoretical ice thickness at Point Barrow, Alaska.

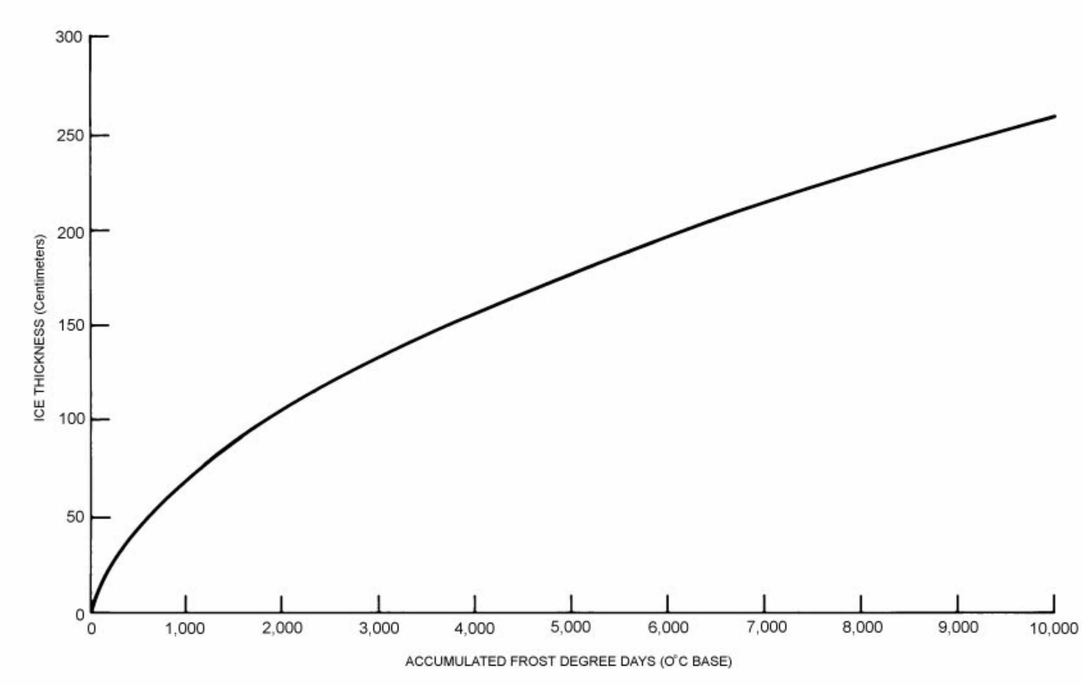


Figure 3404b. Relationship between accumlated frost degree days (°C) and ice thickness (cm).

ice conditions when the temperature gradient through the ice is linear, generally true for ice less than 100 centimeters thick. Differences in predicted thicknesses between models generally reflect differences in environmental parameters (snowfall, heat content of the underlying water column, etc.) at the measurement site. As a result, such equations must be considered partially site specific and their general use approached with caution. For example, applying an equation derived from central Arctic data to coastal conditions or to Antarctic conditions could lead to substantial errors. For this reason Zubov's formula is widely cited as it represents an average of many years of observations from the Russian Arctic:

$$h^2 + 50h = 8\phi$$

where *h* is the ice thickness in centimeters for a given day and ϕ is the cumulative number of frost degree days in degrees Celsius since the beginning of the freezing season.

A frost degree day is defined as a day with a mean temperature of 1° below an arbitrary base. The base most commonly used is the freezing point of freshwater (0°C). If, for example, the mean temperature on a given day is 5° below freezing, then five frost degree days are noted for that day. These frost degree days are then added to those noted the next day to obtain an accumulated value, which is then added to those noted the following day. This process is repeated daily throughout the ice growing season. Temperatures usually fluctuate above and below freezing for several days before remaining below freezing. Therefore, frost degree day accumulations are initiated on the first day of the period when temperatures remain below freezing. The relationship between frost degree day accumulations and theoretical ice growth curves at Point Barrow, Alaska is shown in Figure 3404a. Similar curves for other Arctic stations are contained in publications available from the U.S. Naval Oceanographic Office and the National Ice Center. Figure 3404b graphically depicts the relationship between accumulated frost degree days (°C) and ice thickness in centimeters.

During winter, the ice usually becomes covered with snow, which insulates the ice beneath and tends to slow down its rate of growth. This thickness of snow cover varies considerably from region to region as a result of differing climatic conditions. Its depth may also vary widely within very short distances in response to variable winds and ice topography. While this snow cover persists, about 80 to 85 percent of the incoming radiation is reflected back to space. Eventually, however, the snow begins to melt, as the air temperature rises above 0°C in early summer and the resulting freshwater forms puddles on the surface. These puddles absorb about 90 percent of the incoming radiation and rapidly enlarge as they melt the surrounding snow or ice. Eventually the puddles penetrate to the bottom surface of the floes and as **thawholes**. This slow process is characteristic of ice in the Arctic Ocean and seas where movement is restricted by the coastline or islands. Where ice is free to drift into warmer waters (e.g., the Antarctic, East Greenland, and the Labrador Sea), decay is accelerated in response to wave erosion as well as warmer air and sea temperatures.

3405. Salinity Of Sea Ice

Sea ice forms first as salt-free crystals near the surface

of the sea. As the process continues, these crystals are joined together and, as they do so, small quantities of brine are trapped within the ice. On the average, new ice 15 centimeters thick contains 5 to 10 parts of salt per thousand. With lower temperatures, freezing takes place faster. With faster freezing, a greater amount of salt is trapped in the ice.

Depending upon the temperature, the trapped brine may either freeze or remain liquid, but because its density is greater than that of the pure ice, it tends to settle down through the pure ice. As it does so, the ice gradually freshens, becoming clearer, stronger, and more brittle. At an age of 1 year, sea ice is sufficiently fresh that its melt water, if found in puddles of sufficient size, and not contaminated by spray from the sea, can be used to replenish the freshwater supply of a ship. However, ponds of sufficient size to water ships are seldom found except in ice of great age, and then much of the meltwater is from snow which has accumulated on the surface of the ice. When sea ice reaches an age of about 2 years, virtually all of the salt has been eliminated. Icebergs, having formed from precipitation, contain no salt, and uncontaminated melt water obtained from them is fresh.

The settling out of the brine gives sea ice a honeycomb structure which greatly hastens its disintegration when the temperature rises above freezing. In this state, when it is called **rotten ice**, much more surface is exposed to warm air and water, and the rate of melting is increased. In a day's time, a floe of apparently solid ice several inches thick may disappear completely.

3406. Density Of Ice

The density of freshwater ice at its freezing point is 0.917gm/cm^3. Newly formed sea ice, due to its salt content, is more dense, 0.925 gm/cm^3 being a representative value. The density decreases as the ice freshens. By the time it has shed most of its salt, sea ice is less dense than freshwater ice, because ice formed in the sea contains more air bubbles. Ice having no salt but containing air to the extent of 8 percent by volume (an approximately maximum value for sea ice) has a density of 0.845 gm/cm^3.

The density of land ice varies over even wider limits. That formed by freezing of freshwater has a density of 0.917gm/cm^3, as stated above. Much of the land ice, however, is formed by compacting of snow. This results in the entrapping of relatively large quantities of air. **Névé**, a snow which has become coarse grained and compact through temperature change, forming the transition stage to glacier ice, may have an air content of as much as 50 percent by volume. By the time the ice of a glacier reaches the sea, its density approaches that of freshwater ice. A sample taken from an iceberg on the Grand Banks had a density of 0.899gm/cm^3.

When ice floats, part of it is above water and part is below the surface. The percentage of the mass below the surface can be found by dividing the average density of the ice by the density of the water in which it floats. Thus, if an iceberg of density 0.920 floats in water of density 1.028 (corresponding to a salinity of 35 parts per thousand and a temperature of –1°C), 89.5 percent of its mass will be below the surface.

The height to draft ratio for a blocky or tabular iceberg probably varies fairly closely about 1:5. This average ratio was computed for icebergs south of Newfoundland by considering density values and a few actual measurements, and by seismic means at a number of locations along the edge of the Ross Ice Shelf near Little America Station. It was also substantiated by density measurements taken in a nearby hole drilled through the 256-meter thick ice shelf. The height to draft ratios of icebergs become significant when determining their drift.

3407. Drift Of Sea Ice

Although surface currents have some affect upon the drift of pack ice, the principal factor is wind. Due to Coriolis force, ice does not drift in the direction of the wind, but varies from approximately 18° to as much as 90° from this direction, depending upon the force of the surface wind and the ice thickness. In the Northern Hemisphere, this drift is to the right of the direction toward which the wind blows, and in the Southern Hemisphere it is toward the left. Although early investigators computed average angles of approximately 28° or 29° for the drift of close multiyear pack ice, large drift angles were usually observed with low, rather than high, wind speeds. The relationship between surface wind speed, ice thickness, and drift angle was derived theoretically for the drift of consolidated pack under equilibrium (a balance of forces acting on the ice) conditions, and shows that the drift angle increases with increasing ice thickness and decreasing surface wind speed. A slight increase also occurs with higher latitude.

Since the cross-isobar deflection of the surface wind over the oceans is approximately 20°, the deflection of the ice varies, from approximately along the isobars to as much as 70° to the right of the isobars, with low pressure on the left and high pressure on the right in the Northern Hemisphere. The positions of the low and high pressure areas are, of course, reversed in the Southern Hemisphere.

The rate of drift depends upon the roughness of the surface and the concentration of the ice. Percentages vary from approximately 0.25 percent to almost 8 percent of the surface wind speed as measured approximately 6 meters above the ice surface. Low concentrations of heavily ridged or hummocked floes drift faster than high concentrations of lightly ridged or hummocked floes with the same wind speed. Sea ice of 8 to 9 tenths concentrations and six tenths hummocking or close multiyear ice will drift at approximately 2 percent of the surface wind speed. Additionally, the response factors of 1 and 5 tenths ice concentrations, respectively, are approximately three times and twice the magnitude of the response factor for 9 tenths ice concentrations with the same extent of surface roughness. Isolated ice floes have been observed to drift as fast as 10 percent to 12 percent of strong surface winds.

The rates at which sea ice drifts have been quantified

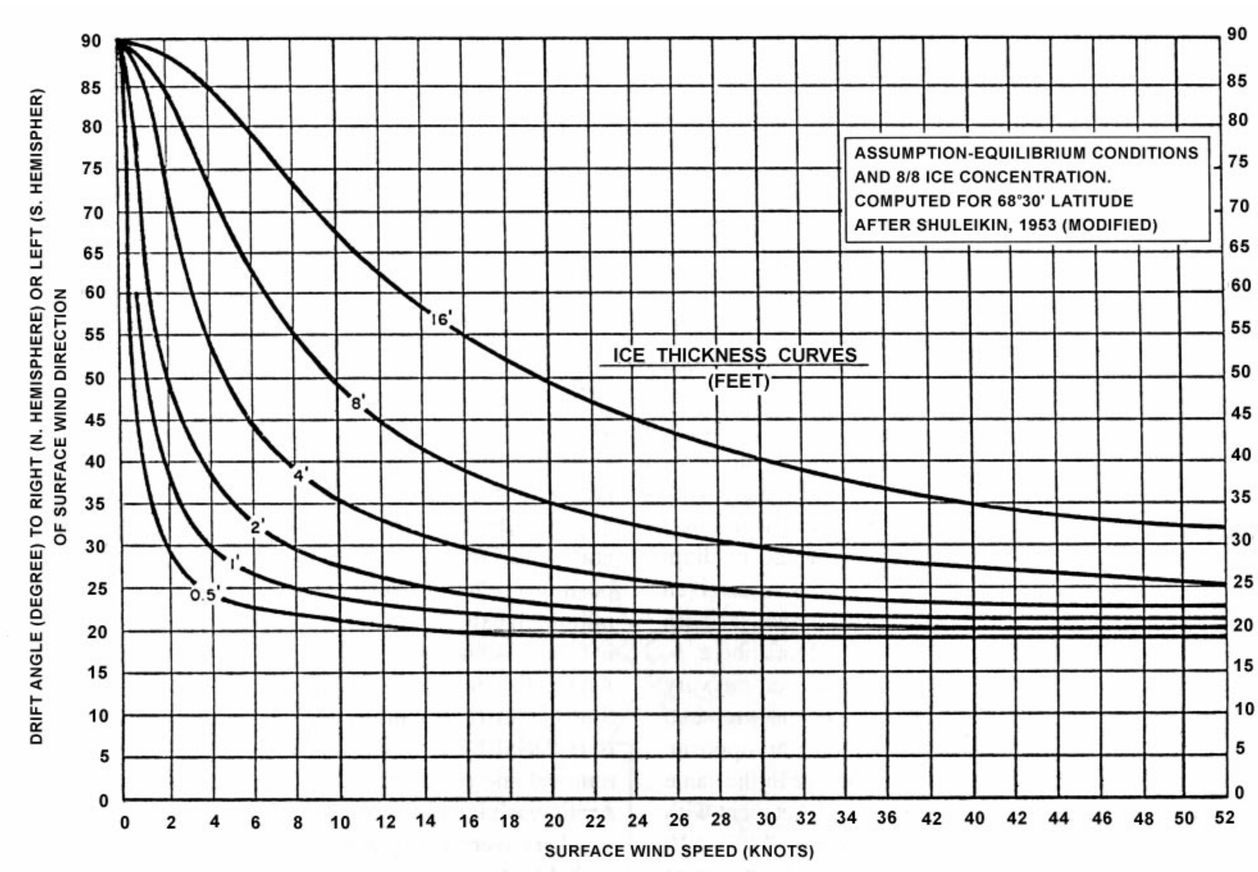


Figure 3407. Ice drift direction for varying wind speed and ice thickness.

through empirical observation. The drift angle, however, has been determined theoretically for 10 tenths ice concentration. This relationship presently is extended to the drift of all ice concentrations, due to the lack of basic knowledge of the dynamic forces that act upon, and result in redistribution of sea ice, in the polar regions.

3408. Iceberg Drift

Icebergs extend a considerable distance below the surface and have relatively small “sail areas” compared to their subsurface mass. Therefore, the near-surface current is thought to be primarily responsible for drift; however, observations have shown that wind can be the dominant force that governs iceberg drift at a particular location or time. Also, the current and wind may contribute nearly equally to the resultant drift.

Two other major forces which act on a drifting iceberg are the Coriolis force and, to a lesser extent, the pressure gradient force which is caused by gravity owing to a tilt of the sea surface, and is important only for iceberg drift in a major current. Near-surface currents are generated by a variety of factors such as horizontal pressure gradients owing to density variations in the water, rotation of the earth, gravitational attraction of the moon, and slope of the sea surface. Wind not only acts directly on an iceberg, but also indirectly by generating waves and a surface current in about the same direction as the wind. Because of inertia, an iceberg may continue to move from the influence of wind for some time after the wind stops or changes direction.

The relative influence of currents and winds on the drift of an iceberg varies according to the direction and magnitude of the forces acting on its sail area and subsurface cross-sectional area. The resultant force therefore involves the proportions of the iceberg above and below the sea surface in relation to the velocity and depth of the current, and the velocity and duration of the wind. Studies tend to show that, generally, where strong currents prevail, the current is dominant. In regions of weak currents, however, winds that blow for a number of hours in a steady direction materially affect the drift of icebergs. Generally, it can be stated that currents tend to have a greater effect on deep-draft icebergs, while winds tend to have a greater effect on shallow-draft icebergs.

As icebergs waste through melting, erosion, and calving, observations indicate the height to draft ratio may approach 1:1 during their last stage of decay, when they are referred to as valley, winged, horned, or spired icebergs.

The height to draft ratios found for icebergs in their various stages are presented in Table 3408a. Since wind tends to have a greater effect on shallow than on deep-draft icebergs, the wind can be expected to exert increasing influence on iceberg drift as wastage increases.

Simple equations which precisely define iceberg drift cannot be formulated at present because of the uncertainty in the water and air drag coefficients associated with iceberg motion. Values for these parameters not only vary from iceberg to iceberg, but they probably change for the same iceberg over its period of wastage.

Present investigations utilize an analytical approach, facilitated by computer calculations, in which the air and water drag coefficients are varied within reasonable limits. Combinations of these drag values are then used in several increasingly complex water models that try to duplicate observed iceberg trajectories. The results indicate that with a wind-generated current, Coriolis force, and a uniform wind, but without a gradient current, small and medium icebergs will drift with the percentages of the wind as given in Table 3408b. The drift will be to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

When gradient currents are introduced, trajectories vary considerably depending on the magnitude of the wind and current, and whether they are in the same or opposite direction. When a 1-knot current and wind are in the same direction, drift is to the right of both wind and current with drift angles increasing linearly from approximately 5° at 10 knots to 22° at 60 knots. When the wind and a 1-knot current are in opposite directions, drift is to the left of the current, with the angle increasing from approximately 3° at 10 knots, to 20° at 30 knots, and to 73° at 60 knots. As a limiting case for increasing wind speeds, drift may be approximately normal (to the right) to the wind direction. This indicates that the wind generated current is clearly dominating the drift. In general, the various models used demonstrated that a combination of the wind and current was responsible for the drift of icebergs.

3409. Extent Of Ice In The Sea

When an area of sea ice, no matter what form it takes or how it is disposed, is described, it is referred to as **pack ice**. In both polar regions the pack ice is a very dynamic feature, with wide deviations in its extent dependent upon changing oceanographic and meteorological phenomena. In winter the Arctic pack extends over the entire Arctic Ocean, and for a varying distance outward from it; the limits recede considerably during the warmer summer months. The average positions of the seasonal absolute and mean maximum and minimum extents of sea ice in the Arctic region are plotted in Figure 3409a. Each year a large portion of the ice from the Arctic Ocean moves outward between Greenland and Spitsbergen (Fram Strait) into the North Atlantic Ocean and is replaced by new ice. Because of this constant annual removal and replacement of sea ice, relatively little of the Arctic pack ice is more than 10 years old.

Ice covers a large portion of the Antarctic waters and is probably the greatest single factor contributing to the isolation of the Antarctic Continent. During the austral winter

Iceberg type	*Height to draft ratio*
Blocky or tabular	1:5
Rounded or domed	1:4
Picturesque or Greenland (sloping)	1:3
Pinnacled or ridged	1:2
Horned, winged, valley, or spired (weathered)	1:1

Table 3408a. Height to draft ratios for various types of icebergs.

Wind Speed (knots)	*Ice Speed/Wind Speed (percent)*		*Drift Angle (degrees)*	
	Small Berg	*Med. Berg*	*Small Berg*	*Med. Berg*
10	3.6	2.2	12	69
20	3.8	3.1	14	55
30	4.1	3.4	17	36
40	4.4	3.5	19	33
50	4.5	3.6	23	32
60	4.9	3.7	24	31

Table 3408b. Drift of iceberg as percentage of wind speed.

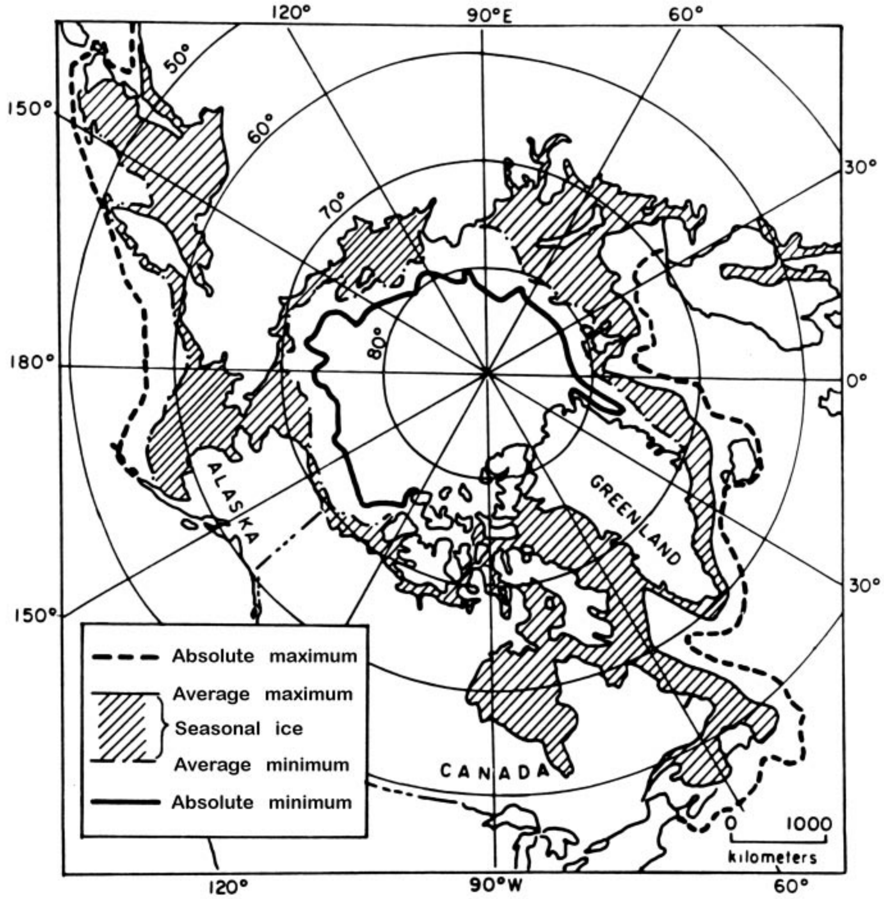


Figure 3409a. Average maximum and minimum extent of Arctic sea ice.

(June through September), ice completely surrounds the continent, forming an almost impassable barrier that extends northward on the average to about 54°S in theAtlantic and to about 62°S in the Pacific. Disintegration of the pack ice during the austral summer months of December through March allows the limits of the ice edge to recede considerably, opening some coastal areas of the Antarctic to navigation. The seasonal absolute and mean maximum and minimum positions of the Antarctic ice limit are shown in Figure 3409b.

Historical information on sea conditions for specific localities and time periods can be found in publications of the Naval Ice Center/National Ice Center (formerly Naval Polar Oceanography Center/U.S. Navy/NOAA Joint Ice Center) and the National Imagery and Mapping Agency (NIMA). National Ice Center (NIC) publications include sea ice annual atlases (1972 to present for Eastern Arctic, Western Arctic and Antarctica), sea ice climatologies, and forecasting guides. NIC sea ice annual atlases include years 1972 to the present for all Arctic and Antarctic seas. NIC ice climatologies describe multiyear statistics for ice extent and coverage. NIC forecasting guides cover procedures for the production of short-term (daily, weekly), monthly, and seasonal predictions. DMAHTC publications include sailing directions which describe localized ice conditions and the effect of ice on Arctic navigation.

3410. Icebergs In The North Atlantic

Sea level glaciers exist on a number of landmasses bordering the northern seas, including Alaska, Greenland, Svalbard (Spitsbergen), Zemlya Frantsa-Iosifa (Franz Josef Land), Novaya Zemlya, and Severnaya Zemlya (Nicholas II Land). Except in Greenland and Franz Josef Land, the rate of calving is relatively slow, and the few icebergs produced melt near their points of formation. Many of those produced along the western coast of Greenland, however, are eventually carried into the shipping lanes of the North Atlantic, where they constitute a major menace to ships. Those calved from Franz Josef Land glaciers drift southwest in the Barents Sea to the vicinity of Bear Island.

Generally the majority of icebergs produced along the

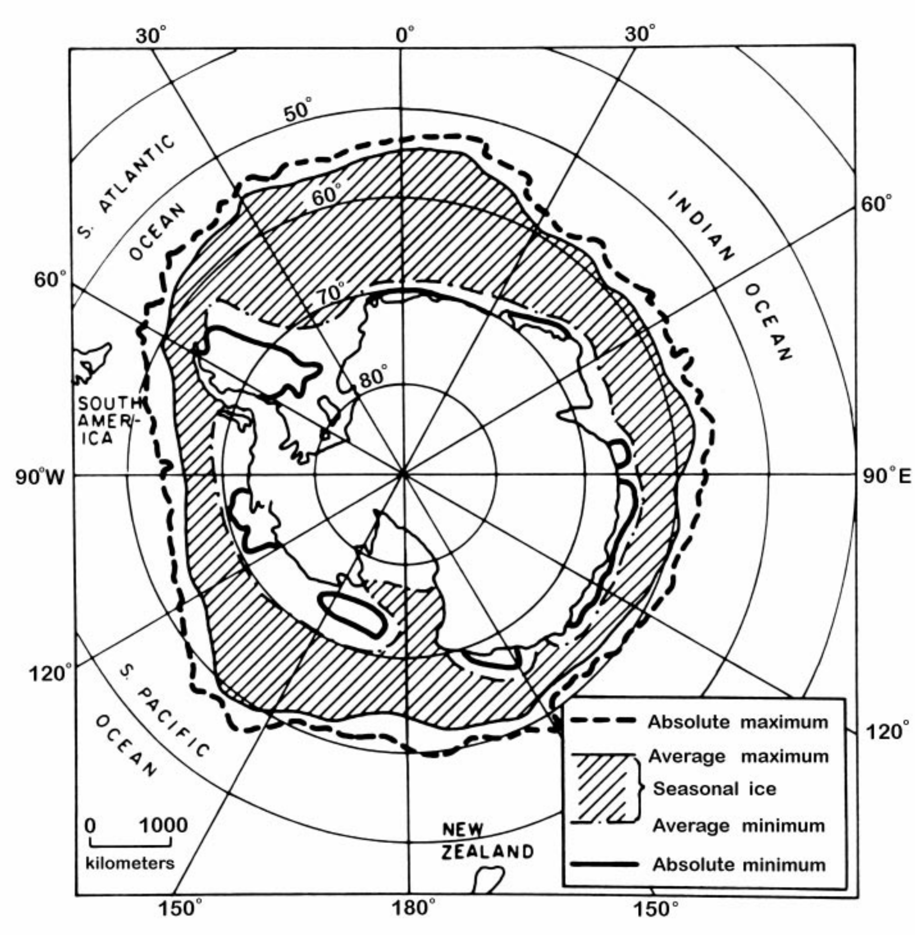


Figure 3409b. Average maximum and minimum extent of Antarctic sea ice.

east coast of Greenland remain near their source. However, a small number of bergy bits, growlers, and small icebergs are transported south from this region by the East Greenland Current around Kap Farvel at the southern tip of Greenland and then northward by the West Greenland Current into Davis Strait to the vicinity of 67°N. Relatively few of these icebergs menace shipping, but some are carried to the south and southeast of Kap Farvel by a counterclockwise current gyre centered near 57°N and 43°W.

The main source of the icebergs encountered in the North Atlantic is the west coast of Greenland between 67°N and 76°N, where approximately 10,000–15,000 icebergs are calved each year. In this area there are about 100 low-lying coastal glaciers, 20 of them being the principal producers of icebergs. Of these 20 major glaciers, 2 located in Disko Bugt between 69°N and 70°N are estimated to contribute 28 percent of all icebergs appearing in Baffin Bay and the Labrador Sea. The West Greenland Current carries icebergs from this area northward and then westward until they encounter the south flowing Labrador Current. West Greenland icebergs generally spend their first winter locked in the Baffin Bay pack ice; however, a large number can also be found within the sea ice extending along the entire Labrador coast by late winter. During the next spring and summer, when they are freed by the break up of the pack ice, they are transported farther southward by the Labrador Current. The general drift patterns of icebergs that are prevalent in the eastern portion of the North American Arctic are shown in Figure 3410a. Observations over a 79-year period show that an average of 427 icebergs per year reach latitudes south of 48°N, with approximately 10 percent of this total carried south of the Grand Banks (43°N) before they melt. Icebergs may be encountered during any part of the year, but in the Grand Banks area they are most numerous during spring. The maximum monthly average of iceberg sightings below 48°N occurs during April, May and June, with May having the highest average of 129.

The variation from average conditions is considerable. More than 2,202 icebergs have been sighted south of latitude 48°N in a single year (1984), while in 1966 not a single iceberg was encountered in this area. In the years of 1940 and 1958, only one iceberg was observed south of 48°N. The length of the iceberg "season" as defined by the International Ice Patrol also varies considerably, from 97

days in 1965 to 203 days in 1992, with an average length of 132 days. Although this variation has not been fully explained, it is apparently related to wind conditions, the distribution of pack ice in Davis Strait, and to the amount of pack ice off Labrador. It has been suggested that the distribution of the Davis Strait-Labrador Sea pack ice influences the melt rate of the icebergs as they drift south. Sea ice will decrease iceberg erosion by damping waves and holding surface water temperatures below 0°C, so as the areal extent of the sea ice increases the icebergs will tend to survive longer.

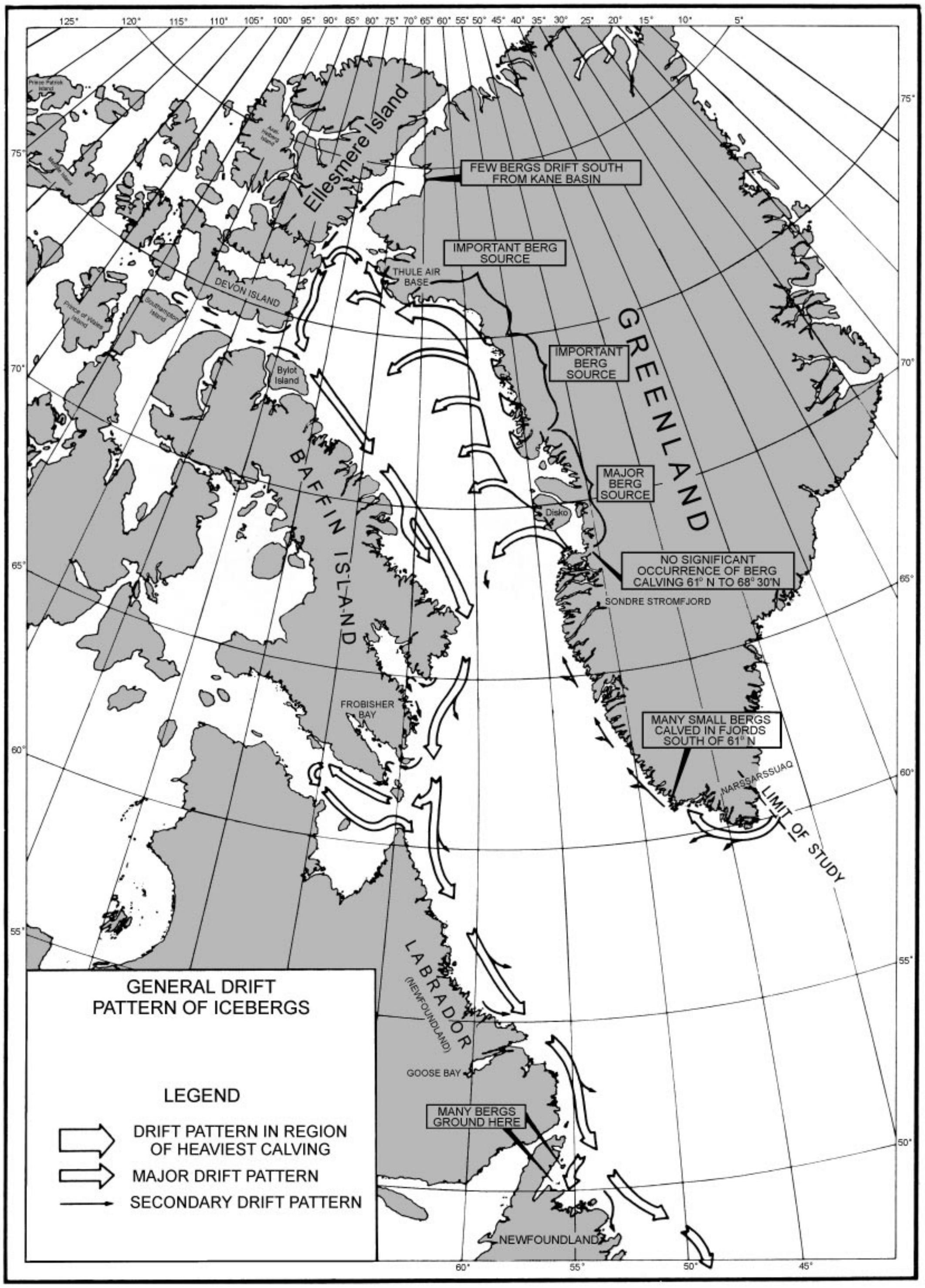


Figure 3410a. General drift pattern of icebergs.

Stronger than average northerly or northeasterly winds during late winter and spring will enhance sea ice drift to the south, which also may lengthen iceberg lifetimes. There are also large interannual variations in the number of icebergs calved from Greenland's glaciers, so the problem of forecasting the length and severity of an iceberg season is exceedingly complex.

Average iceberg and pack ice limits in this area during May are shown in Figure 3410b. Icebergs have been observed in the vicinity of Bermuda, the Azores, and within 400 to 500 kilometers of Great Britain.

Pack ice may also be found in the North Atlantic, some having been brought south by the Labrador Current and some coming through Cabot Strait after having formed in the Gulf of St. Lawrence.

3411. The International Ice Patrol

The International Ice Patrol was established in 1914 by the *International Convention for the Safety of Life at Sea* (SOLAS), held in 1913 as a result of the sinking of the RMS *Titanic* in 1912. The *Titanic* struck an iceberg on its maiden voyage and sank with the loss of 1,513 lives. In accordance with the agreement reached at the SOLAS conventions of 1960 and 1974, the International Ice Patrol is conducted by the U.S. Coast Guard, which is responsible for the observation and dissemination of information concerning ice conditions in the North Atlantic. Information on ice conditions for the Gulf of St. Lawrence and the coastal waters of Newfoundland and Labrador, including the Strait of Belle Isle, is provided by ECAREG Canada (Eastern Canada Traffic System), through any Coast Guard Radio Station, from the month of December through late June. Sea ice data for these areas can also be obtained from the Ice Operations Officer, located at Dartmouth, Nova Scotia, via Sydney, Halifax, or St. John's marine radio.

During the war years of 1916-18 and 1941-45, the Ice Patrol was suspended. Aircraft were added to the patrol force

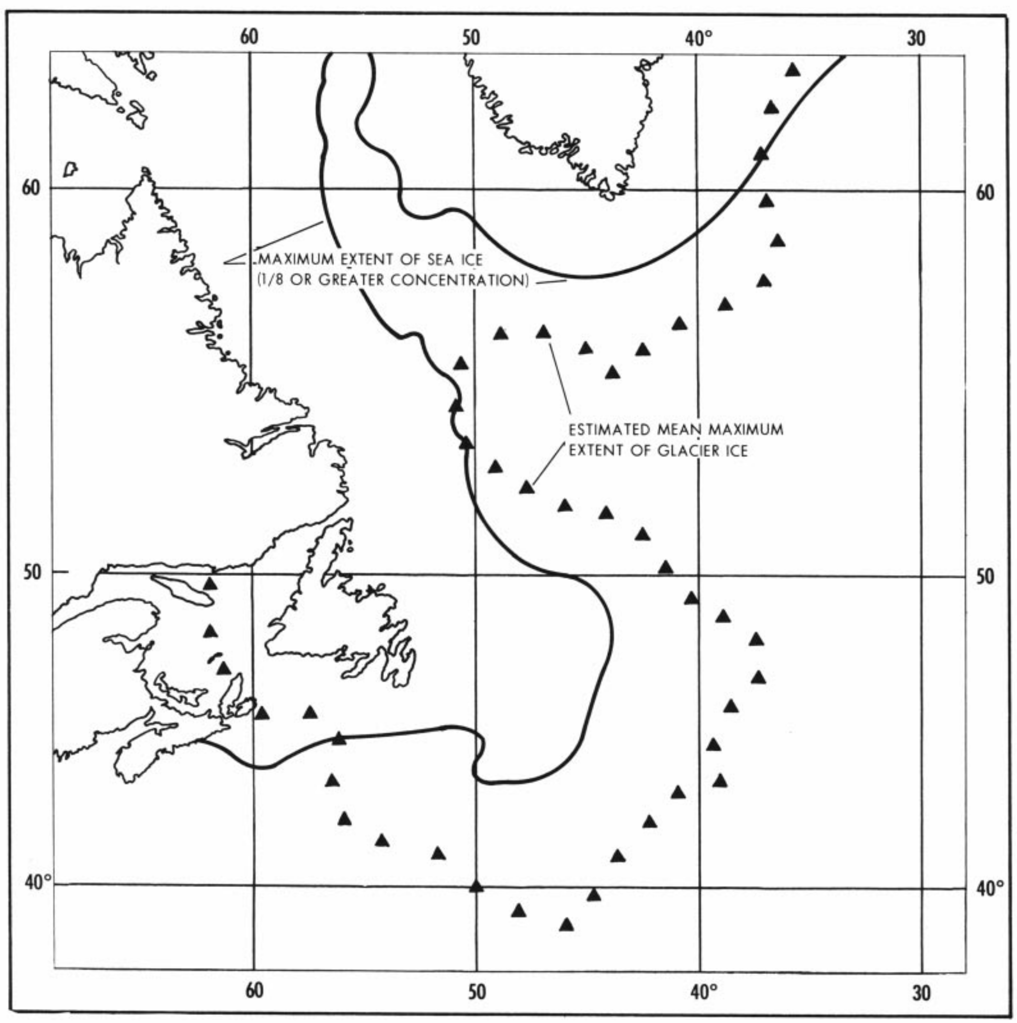


Figure 3410b. Average iceberg and pack ice limits during the month of May.

following World War II, and today perform the majority of the reconnaissance work. During each ice season, aerial reconnaissance surveys are made in the vicinity of the Grand Banks off Newfoundland to determine the southeastern, southern, and southwestern limit of the seaward extent of icebergs. The U.S. Coast Guard aircraft use Side-Looking Airborne Radar (SLAR) as well as Forward-Looking Airborne Radar (FLAR) to help detect and identify icebergs in this notoriously fog-ridden area. Reports of ice sightings are also requested and collected from ships transiting the Grand Banks area. When reporting ice, vessels are requested to detail the concentration and stage of development of sea ice, number of icebergs, the bearing of the principal sea ice edge, and the present ice situation and trend over the preceding three hours. These five parameters are part of the ICE group of the ship synoptic code which is addressed in more detail in Section 3416 on ice observation. In addition to ice reports, masters who do not issue routine weather reports are urged to make sea surface temperature and weather reports to the Ice Patrol every six hours when within latitudes 40° to 52°N and longitudes 38° to 58°W (the Ice Patrol Operations Area). Ice reports may be sent at no charge using INMARSAT Code 42.

The Ice Patrol activities are directed from an Operations Center at Avery Point, Groton, Connecticut. The Ice Patrol gathers all sightings and puts them into a computer model which analyzes and predicts iceberg drift and deterioration. Due to the large size of the Ice Patrol's operations area, icebergs are infrequently resighted. The model predictions are crucial to setting the limits of all known ice. The fundamental model force balance is between iceberg acceleration and accelerations due to air and water drag, the Coriolis force, and a sea surface slope term. The model is primarily driven by a water current that combines a depth- and time-independent geostrophic (mean) current with a depth- and time-dependent current driven by the wind (Ekman flow).

Environmental parameters for the model, including sea surface temperature, wave height and period, and wind, are obtained from the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, California every 12 hours. The International Ice Patrol also deploys from 12–15 World Ocean Circulation Experiment (WOCE) drifting buoys per year, and uses the buoy drifts to alter the climatological mean (geostrophic) currents used by the model in the immediate area of the buoys. The buoy drift data have been archived at the National Oceanographic Data Center (NODC) and are available for use by researchers outside the Coast Guard. Sea surface temperature, wave height and wave period are the main forces determining the rate of iceberg deterioration. Ship observations of these variables are extremely important in making model inputs more accurately reflect actual situations.

The results from the iceberg drift and deterioration model are used to compile bulletins that are issued twice daily during the ice season by radio communications from Boston, Massachusetts; St. John's, Newfoundland; and other radio stations. Bulletins are also available over INMARSAT. When icebergs are sighted outside the known limits of ice, special safety broadcasts are issued in between the regularly scheduled bulletins. Iceberg positions in the ice bulletins are updated for drift and deterioration at 12-hour intervals. A radio-facsimile chart is also broadcast twice a day throughout the ice season. A summary of broadcast times and frequencies is found in *Pub. 117, Radio Navigational Aids*.

The Ice Patrol, in addition to patrolling possible iceberg areas, conducts oceanographic surveys, maintains up-to-date records of the currents in its area of operation to aid in predicting the drift of icebergs, and studies iceberg conditions in general.

3412. Ice Detection

Safe navigation in the polar seas depends on a number of factors, not the least of which is accurate knowledge of the location and amount of sea ice that lies between the mariner and his destination. Sophisticated electronic equipment, such as radar, sonar, and the visible, infrared, and microwave radiation sensors on board satellites, have added to our ability to detect and thus avoid ice.

As a ship proceeds into higher latitudes, the first ice encountered is likely to be in the form of icebergs, because such large pieces require a longer time to disintegrate. Icebergs can easily be avoided if detected soon enough. The distance at which an iceberg can be seen visually depends upon meteorological visibility, height of the iceberg, source and condition of lighting, and the observer. On a clear day with excellent visibility, a large iceberg might be sighted at a distance of 20 miles. With a low-lying haze around the horizon, this distance will be reduced. In light fog or drizzle this distance is further reduced, down to near zero in heavy fog.

In a dense fog an iceberg may not be perceptible until it is close aboard where it will appear in the form of a luminous, white object if the sun is shining; or as a dark, somber mass with a narrow streak of blackness at the waterline if the sun is not shining. If the layer of fog is not too thick, an iceberg may be sighted from aloft sooner than from a point lower on the vessel, but this does not justify omitting a bow lookout. The diffusion of light in a fog will produce a **blink**, or area of whiteness, above and at the sides of an iceberg which will appear to increase the apparent size of its mass.

On dark, clear nights icebergs may be seen at a distance of from 1 to 3 miles, appearing either as white or black objects with occasional light spots where waves break against it. Under such conditions of visibility growlers are a greater menace to vessels; the vessel's speed should be reduced and a sharp lookout maintained.

The moon may either help or hinder, depending upon its phase and position relative to ship and iceberg. A full moon

in the direction of the iceberg interferes with its detection, while moonlight from behind the observer may produce a blink which renders the iceberg visible for a greater distance, as much as 3 or more miles. A clouded sky at night, through which the moonlight is intermittent, also renders ice detection difficult. A night sky with heavy passing clouds may also dim or obscure any object which has been sighted, and fleecy cumulus and cumulonimbus clouds often may give the appearance of blink from icebergs.

If an iceberg is in the process of disintegration, its presence may be detected by a cracking sound as a piece breaks off, or by a thunderous roar as a large piece falls into the water. These sounds are unlikely to be heard due to shipboard noise. The appearance of small pieces of ice in the water often indicates the presence of an iceberg nearby. In calm weather these pieces may form a curved line with the parent iceberg on the concave side. Some of the pieces broken from an iceberg are themselves large enough to be a menace to ships.

As the ship moves closer towards areas known to contain sea ice, one of the most reliable signs that pack ice is being approached is the absence of swell or wave motion in a fresh breeze or a sudden flattening of the sea, especially from leeward. The observation of icebergs is not a good indication that pack ice will be encountered soon, since icebergs may be found at great distances from pack ice. If the sea ice is approached from windward, it is usually compacted and the edge will be sharply defined. However, if it is approached from leeward, the ice is likely to be loose and somewhat scattered, often in long narrow arms.

Another reliable sign of the approach of pack ice not yet in sight is the appearance of a pattern, or **sky map**, on the horizon or on the underside of distant, extensive cloud areas, created by the varying amounts of light reflected from different materials on the sea or earth's surface. A bright white glare, or **snow blink**, will be observed above a snow covered surface. When the reflection on the underside of clouds is caused by an accumulation of distant ice, the glare is a little less bright and is referred to as an **ice blink**. A relatively dark pattern is reflected on the underside of clouds when it is over land that is not snow covered. This is known as a **land sky**. The darkest pattern will occur when the clouds are above an open water area, and is called a **water sky**. A mariner experienced in recognizing these sky maps will find them useful in avoiding ice or searching out openings which may permit his vessel to make progress through an ice field.

Another indication of the presence of sea ice is the formation of thick bands of fog over the ice edge, as moisture condenses from warm air when passing over the colder ice. An abrupt change in air or sea temperature or seawater salinity is *not* a reliable sign of the approach of icebergs or pack ice.

The presence of certain species of animals and birds can also indicate that pack ice is in close proximity. The sighting of walruses, seals, or polar bears in the Arctic should warn the mariner that pack ice is close at hand. In the Antarctic, the usual precursors of sea ice are penguins, terns, fulmars, petrels, and skuas.

When visibility becomes limited, radar can prove to be an invaluable tool for the polar mariner. Although many icebergs will be observed visually on clear days before there is a return on the radarscope, radar under bad weather conditions will detect the average iceberg at a range of about 8 to 10 miles. The intensity of the return is a function of the nature of the iceberg's exposed surface (slope, surface roughness); however, it is unusual to find an iceberg which will not produce a detectable echo.

Large, vertical-sided tabular icebergs of the Antarctic and Arctic ice islands are usually detected by radar at ranges of 15 to 30 miles; a range of 37 miles has been reported.

Whereas a large iceberg is almost always detected by radar in time to be avoided, a growler large enough to be a serious menace to a vessel may be lost in the sea return and escape detection. If an iceberg or growler is detected by radar, tracking is sometimes necessary to distinguish it from a rock, islet, or another ship.

Radar can be of great assistance to an experienced radar observer. Smooth sea ice, like smooth water, returns little or no echo, but small floes of rough, hummocky sea ice capable of inflicting damage to a ship can be detected in a smooth sea at a range of about 2 to 4 miles. The return may be similar to sea return, but the same echoes appear at each sweep. A lead in smooth ice is clearly visible on a radarscope, even though a thin coating of new ice may have formed in the opening. A light covering of snow obliterating many of the features to the eye has little effect upon a radar return. The ranges at which ice can be detected by radar are somewhat dependent upon refraction, which is sometimes quite abnormal in polar regions. Experience in interpretation is gained through comparing various radar returns with actual observations.

Echoes from the ship's whistle or horn may sometimes indicate the presence of icebergs and can give an indication of direction. If the time interval between the sound and its echo is measured, the distance in meters can be determined by multiplying the number of seconds by 168. However, echoes are very unreliable reliable because only ice with a large vertical area facing the ship returns enough echo to be heard. Once an echo is heard, a distinct pattern of horn blasts (not a Navigational Rules signal) should be made to confirm that the echo is not another vessel.

At relatively short ranges, sonar is sometimes helpful in locating ice. The initial detection of icebergs may be made at a distance of about 3 miles or more, but usually considerably less. Growlers may be detected at a distance of $^1/_2$ to 2 miles, and even smaller pieces may be detected in time to avoid them.

Ice in the polar regions is best detected and observed from the air, either from aircraft or by satellite. Fixed-winged aircraft have been utilized extensively for obtaining detailed aerial ice reconnaissance information since the early 1930's, and will no doubt continue to provide this invaluable service for many years to come. Some ships, particularly icebreakers, proceeding into high latitudes car-

ry helicopters, which are invaluable in locating leads and determining the relative navigability of different portions of the ice pack. Ice reports from personnel at Arctic and Antarctic coastal shore stations can also prove valuable to the polar mariner.

The enormous ice reconnaissance capabilities of meteorological satellites were confirmed within hours of the launch by the National Aeronautics and Space Administration (NASA) of the first experimental meteorological satellite, TIROS I, on April 1, 1960. With the advent of the polar-orbiting meteorological satellites during the mid and late 1960's, the U.S. Navy initiated an operational satellite ice reconnaissance program which could observe ice and its movement in any region of the globe on a daily basis, depending upon solar illumination. Since then, improvements in satellite sensor technology have provided a capability to make detailed global observations of ice properties under all weather and lighting conditions. The current suite of airborne and satellite sensors employed by the National Ice Center include: aerial reconnaissance including visual and Side-Looking Airborne Radar (SCAR), TIROS AVHRR visual and infrared, Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) visual and infrared, all-weather passive microwave from the DMSP Special Sensor Microwave Imager (SSM/I) and the ERS-1 Synthetic Aperture Radar (SAR). Examples of satellite imagery of ice covered waters are shown in Figure 3412a and Figure 3412b.

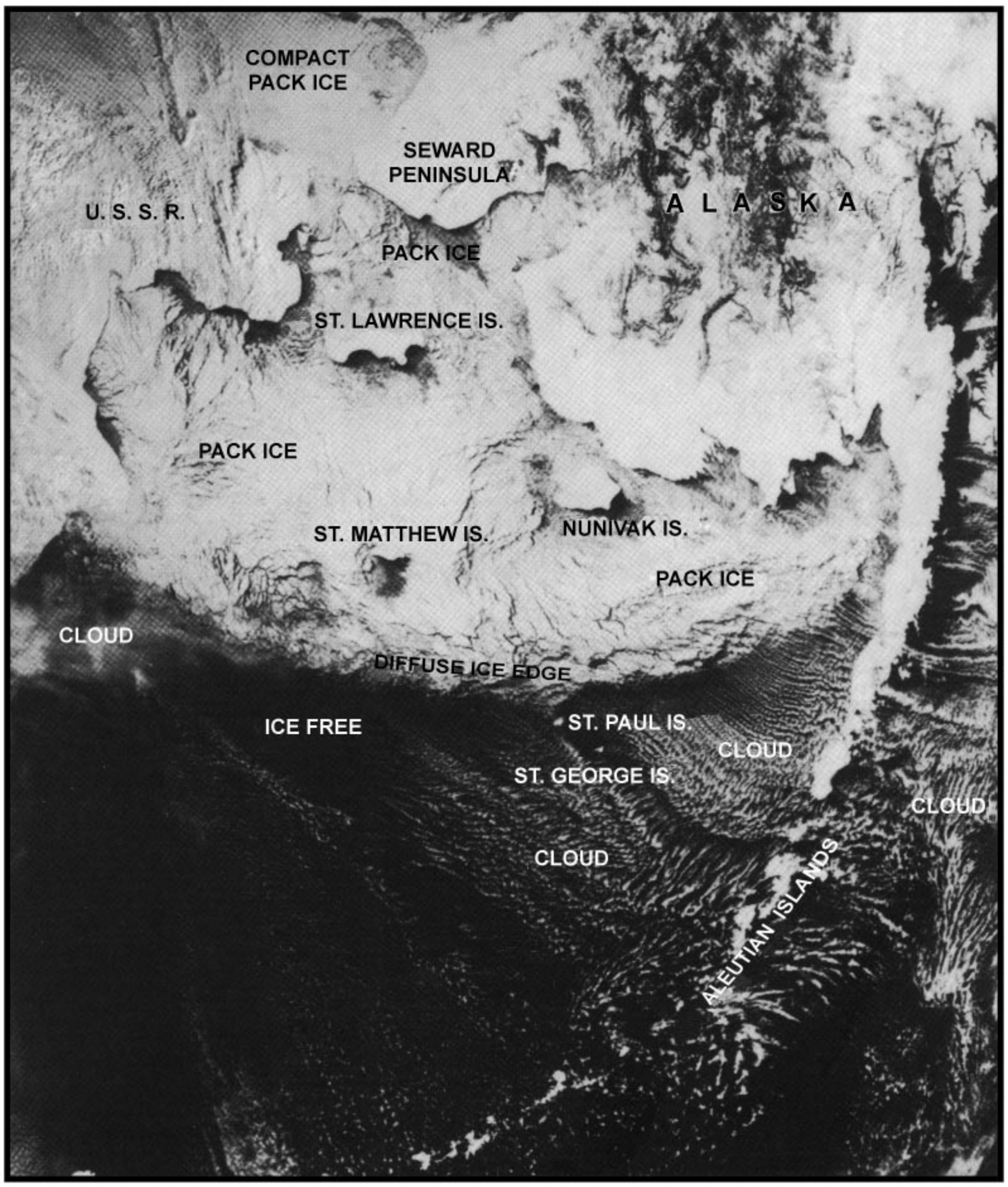


Figure 3412a. Example of satellite imagery with a resolution of 0.9 kilometer.

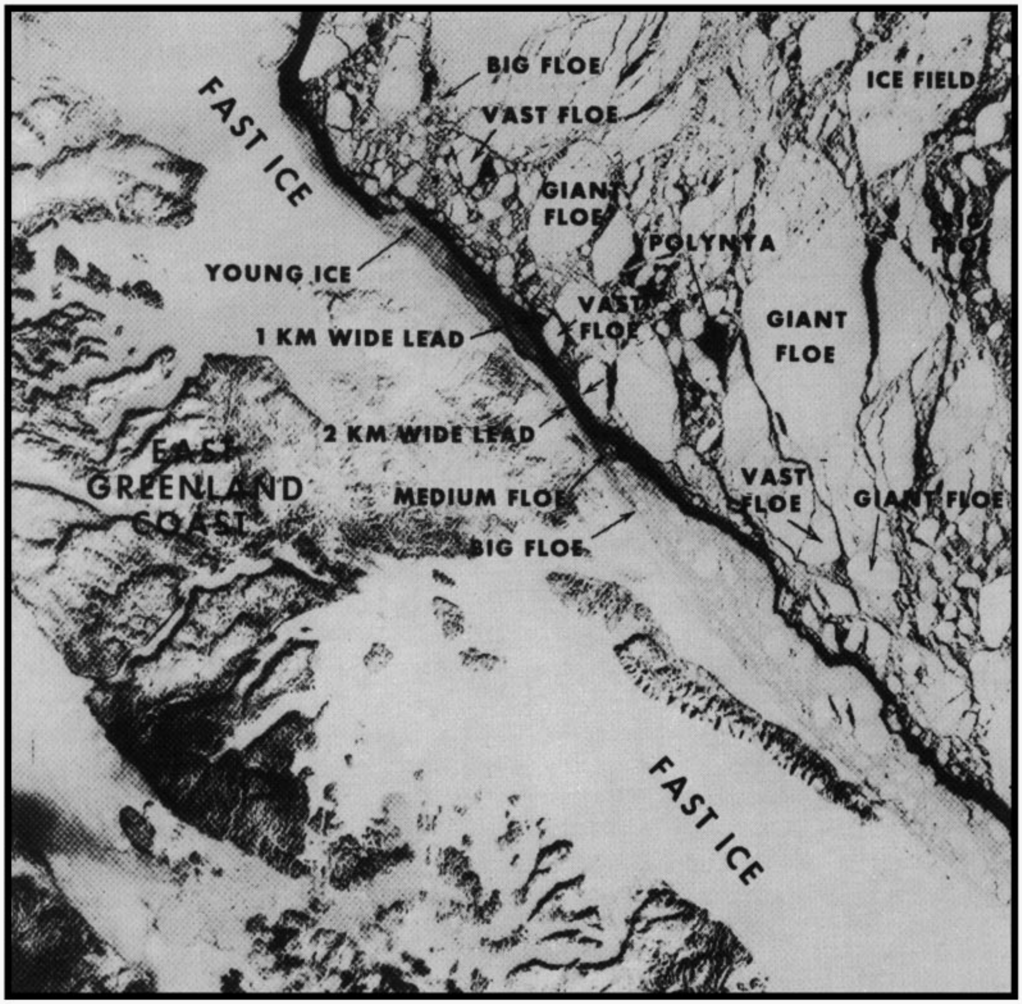


Figure 3412b. Example of satellite imagery with a resolution of 80 meters.

3413. Operations In Ice

Operations in ice-prone regions necessarily require considerable advanced planning and many more precautionary measures than those taken prior to a typical open ocean voyage. The crew, large or small, of a polar-bound vessel should be thoroughly indoctrinated in the fundamentals of polar operations, utilizing the best information sources available. The subjects covered should include training in ship handling in ice, polar navigation, effects of low temperatures on materials and equipment, damage control procedures, communications problems inherent in polar regions, polar meteorology, sea ice terminology, ice observing and reporting procedures (including classification and codes) and polar survival. Training materials should consist of reports on previous Arctic and Antarctic voyages, sailing directions, ice atlases, training films on polar operations, and U.S. Navy service manuals detailing the recommended procedures to follow during high latitude missions. Various sources of information can be obtained from the Director, National Ice Center, 4251 Suitland Road, Washington, D.C., 20395 and from the Office of Polar Programs, National Science Foundation, Washington, D.C.

The preparation of a vessel for polar operations is of extreme importance and the considerable experience gained from previous operations should be drawn upon to bring the ship to optimum operating condition. At the very least, operations conducted in ice-infested waters require that the vessel's hull and propulsion system undergo certain modifications.

The bow and waterline of the forward part of the vessel should be heavily reinforced. Similar reinforcement should also be considered for the propulsion spaces of the vessel. Cast iron propellers and those made of a bronze alloy do not possess the strength necessary to operate safely in ice. Therefore, it is strongly recommended that propellers made of these materials be replaced by steel. Other desirable features are the absence of vertical sides, deep placement of

the propellers, a blunt bow, metal guards to protect propellers from ice damage, and lifeboats for 150 percent of personnel aboard. The complete list of desirable features depends upon the area of operations, types of ice to be encountered, length of stay in the vicinity of ice, anticipated assistance by icebreakers, and possibly other factors. Strength requirements and the minimum thicknesses deemed necessary for the vessel's frames and additional plating to be used as reinforcement, as well as other procedures needed to outfit a vessel for ice operations, can be obtained from the American Bureau of Shipping. For a more definitive and complete guide to the ice strengthening of ships, the mariner may desire to consult the procedures outlined in Rules for Ice Strengthening of Ships, from the Board of Navigation, Helsinki, Finland.

Equipment necessary to meet the basic needs of the crew and to insure the successful and safe completion of the polar voyage should not be overlooked. A minimum list of essential items should consist of polar clothing and footwear, 100% u/v protection sunglasses, food, vitamins, medical supplies, fuel, storage batteries, antifreeze, explosives, detonators, fuses, meteorological supplies, and survival kits containing sleeping bags, trail rations, firearms, ammunition, fishing gear, emergency medical supplies, and a repair kit.

The vessel's safety depends largely upon the thoroughness of advance preparations, the alertness and skill of its crew, and their ability to make repairs if damage is incurred. Spare propellers, rudder assemblies, and patch materials, together with the equipment necessary to effect emergency repairs of structural damage should be carried. Examples of repair materials needed include quick setting cement, oakum, canvas, timbers, planks, pieces of steel of varying shapes, welding equipment, clamps, and an assortment of nuts, bolts, washers, screws, and nails.

Ice and snow accumulation on the vessel poses a definite capsize hazard. Mallets, baseball bats, ax handles, and scrapers to aid in the removal of heavy accumulations of ice, together with snow shovels and stiff brooms for snow removal should be provided. A live steam line may be useful in removing ice from superstructures.

Navigation in polar waters is at best difficult and, during poor conditions, impossible. Environmental conditions encountered in high latitudes such as fog, storms, compass anomalies, atmospheric effects, and, of course, ice, hinder polar operations. Also, deficiencies in the reliability and detail of hydrographic and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data, add to the problems of polar navigation. Much work is being carried out in polar regions to improve the geodetic control, triangulation, and quality of hydrographic and topographic information necessary for accurate polar charts. However, until this massive task is completed, the only resource open to the polar navigator, especially during periods of poor environmental conditions, is to rely upon the basic principles of navigation and adapt them to unconventional methods when abnormal situations arise.

Upon the approach to pack ice, a careful decision is needed to determine the best action. Often it is possible to go around the ice, rather than through it. Unless the pack is quite loose, this action usually gains rather than loses time. When skirting an ice field or an iceberg, do so to windward, if a choice is available, to avoid projecting tongues of ice or individual pieces that have been blown away from the main body of ice.

When it becomes necessary to enter pack ice, a thorough examination of the distribution and extent of the ice conditions should be made beforehand from the highest possible location. Aircraft (particularly helicopters) and direct satellite readouts are of great value in determining the nature of the ice to be encountered. The most important features to be noted include the location of open water, such as leads and polynyas, which may be manifested by water sky; icebergs; and the presence or absence of both ice under pressure and rotten ice. Some protection may be offered the propeller and rudder assemblies by trimming the vessel down by the stern slightly (not more than 2–3 feet) prior to entering the ice; however, this precaution usually impairs the maneuvering characteristics of most vessels not specifically built for ice breaking.

Selecting the point of entry into the pack should be done with great care; and if the ice boundary consists of closely packed ice or ice under pressure, it is advisable to skirt the edge until a more desirable point of entry is located. Seek areas with low ice concentrations, areas of rotten ice or those containing navigable leads, and if possible enter from leeward on a course perpendicular to the ice edge. It is also advisable to take into consideration the direction and force of the wind, and the set and drift of the prevailing currents when determining the point of entry and the course followed thereafter. Due to wind induced wave action, ice floes close to the periphery of the ice pack will take on a bouncing motion which can be quite hazardous to the hull of thin-skinned vessels. In addition, note that pack ice will drift slightly to the right of the true wind in the Northern Hemisphere and to the left in the Southern Hemisphere, and that leads opened by the force of the wind will appear perpendicular to the wind direction. If a suitable entry point cannot be located due to less than favorable conditions, patience may be called for. Unfavorable conditions generally improve over a short period of time by a change in the wind, tide, or sea state.

Once in the pack, always try to work with the ice, not against it, and keep moving, but do not rush. Respect the ice but do not fear it. Proceed at slow speed at first, staying in open water or in areas of weak ice if possible. The vessel's speed may be safely increased after it has been ascertained how well it handles under the varying ice conditions encountered. It is better to make good progress in the general direction desired than to fight large thick floes in the exact direction to be made good. However, avoid the temptation to proceed far to one side of the intended track; it is almost always better to back out and seek a more penetrable area.

During those situations when it becomes necessary to back, always do so with extreme caution and *with the rudder amidships*. If the ship is stopped by ice, the first command should be "rudder amidships," given while the screw is still turning. This will help protect the propeller when backing and prevent ice jamming between rudder and hull. If the rudder becomes ice-jammed, man after steering, establish communications, and *do not* give any helm commands until the rudder is clear. A quick full-ahead burst may clear it. If it does not, try going to "hard rudder" *in the same direction slowly* while turning full or flank speed ahead.

Ice conditions may change rapidly while a vessel is working in pack ice, necessitating quick maneuvering. Conventional vessels, even though ice strengthened, are not built for ice breaking. The vessel should be conned to first attempt to place it in leads or polynyas, giving due consideration to wind conditions. The age, thickness, and size of ice which can be navigated depends upon the type, size, hull strength, and horsepower of the vessel employed. If contact with an ice floe is unavoidable, never strike it a glancing blow. This maneuver may cause the ship to veer off in a direction which will swing the stern into the ice. If possible, seek weak spots in the floe and hit it head-on at slow speed. Unless the ice is rotten or very young, do not attempt to break through the floe, but rather make an attempt to swing it aside as speed is slowly increased. Keep clear of corners and projecting points of ice, but do so without making sharp turns which may throw the stern against the ice, resulting in a damaged propeller, propeller shaft, or rudder. The use of full rudder in non-emergency situations is not recommended because it may swing either the stern or mid-section of the vessel into the ice. This does not preclude use of alternating full rudder (swinging the rudder) aboard ice-breakers as a technique for penetrating heavy ice.

Offshore winds may open relatively ice free navigable coastal leads, but such leads should not be entered without benefit of icebreaker escort. If it becomes necessary to enter coastal leads, narrow straits, or bays, an alert watch should be maintained since a shift in the wind may force drifting ice down upon the vessel. An increase in wind on the windward side of a prominent point, grounded iceberg, or land ice tongue extending into the sea will also endanger a vessel. It is wiser to seek out leads toward the windward side of the main body of the ice pack. In the event that the vessel is under imminent danger of being trapped close to shore by pack ice, immediately attempt to orient the vessel's bow seaward. This will help to take advantage of the little maneuvering room available in the open water areas found between ice floes. Work carefully through these areas, easing the ice floes aside while maintaining a close watch on the general movement of the ice pack.

If the vessel is completely halted by pack ice, it is best to keep the rudder amidships, and the propellers turning at slow speed. The wash of the propellers will help to clear ice away from the stern, making it possible to back down safely. When the vessel is stuck fast, an attempt first should be made to free the vessel by going full speed astern. If this maneuver proves ineffective, it may be possible to get the vessel's stern to move slightly, thereby causing the bow to shift, by quickly shifting the rudder from one side to the other while going full speed ahead. Another attempt at going astern might then free the vessel. The vessel may also be freed by either transferring water from ballast tanks, causing the vessel to list, or by alternately flooding and emptying the fore and aft tanks. A heavy weight swung out on the cargo boom might give the vessel enough list to break free. If all these methods fail, the utilization of deadmen (2– to 4–meter lengths of timber buried in holes out in the ice and to which a vessel is moored) and ice anchors (a stockless, single-fluked hook embedded in the ice) may be helpful. With a deadman or ice anchors attached to the ice astern, the vessel may be warped off the ice by winching while the engines are going full astern. If all the foregoing methods fail, explosives placed in holes cut nearly to the bottom of the ice approximately 10 to 12 meters off the beam of the vessel and detonated while the engines are working full astern might succeed in freeing the vessel. A vessel may also be sawed out of the ice if the air temperature is above the freezing point of seawater.

When a vessel becomes so closely surrounded by ice that all steering control is lost and it is unable to move, it is **beset**. It may then be carried by the drifting pack into shallow water or areas containing thicker ice or icebergs with their accompanying dangerous underwater projections. If ice forcibly presses itself against the hull, the vessel is said to be **nipped**, whether or not damage is sustained. When this occurs, the gradually increasing pressure may be capable of holing the vessel's bottom or crushing the sides. When a vessel is beset or nipped, freedom may be achieved through the careful maneuvering procedures, the physical efforts of the crew, or by the use of explosives similar to those previously detailed. Under severe conditions the mariner's best ally may be patience since there will be many times when nothing can be done to improve the vessel's plight until there is a change in meteorological conditions. It may be well to preserve fuel and perform any needed repairs to the vessel and its engines. Damage to the vessel while it is beset is usually attributable to collisions or pressure exerted between the vessel's hull, propellers, or rudder assembly, and the sharp corners of ice floes. These collisions can be minimized greatly by attempting to align the vessel in such a manner as to insure that the pressure from the surrounding pack ice is distributed as evenly as possible over the hull. This is best accomplished when medium or large ice floes encircle the vessel.

In the vicinity of icebergs, either in or outside of the pack ice, a sharp lookout should be kept and all icebergs given a wide berth. The commanding officers and masters of all vessels, irrespective of their size, should treat all icebergs with great respect. The best locations for lookouts are generally in a crow's nest, rigged in the foremast or housed in a shelter built specifically for a bow lookout in the eyes of a vessel. Telephone communications between these sites and the navigation bridge on larger vessels will prove in-

valuable. It is dangerous to approach close to an iceberg of any size because of the possibility of encountering underwater extensions, and because icebergs that are disintegrating may suddenly capsize or readjust their masses to new positions of equilibrium. In periods of low visibility the utmost caution is needed at all times. Vessel speed should be reduced and the watch prepared for quick maneuvering. Radar becomes an effective tool in this case, but does not negate the need for trained lookouts.

Since icebergs may have from eight to nine-tenths of their masses below the water surface, their drift is generally influenced more by currents than winds, particularly under light wind conditions. The drift of pack ice, on the other hand, is usually dependent upon the wind. Under these conditions, icebergs within the pack may be found moving at a different rate and in a different direction from that of the pack ice. In regions of strong currents, icebergs should always be given a wide berth because they may travel upwind under the influence of contrary currents, breaking heavy pack in their paths and endangering vessels unable to work clear. In these situations, open water will generally be found to leeward of the iceberg, with piled up pack ice to windward. Where currents are weak and a strong wind predominates, similar conditions will be observed as the wind driven ice pack overtakes an iceberg and piles up to windward with an open water area lying to leeward.

Under ice, submarine operations require knowledge of prevailing and expected sea ice conditions to ensure maximum operational efficiency and safety. The most important ice features are the frequency and extent of downward projections (bummocks and ice keels) from the underside of the ice canopy (pack ice and enclosed water areas from the point of view of the submariner), the distribution of thin ice areas through which submarines can attempt to surface, and the probable location of the outer pack edge where submarines can remain surfaced during emergencies to rendezvous with surface ship or helicopter units.

Bummocks are the subsurface counterpart of hummocks, and **ice keels** are similarly related to ridges. When the physical nature of these ice features is considered, it is apparent that ice keels may have considerable horizontal extent, whereas individual bummocks can be expected to have little horizontal extent. In shallow water lanes to the Arctic Basin, such as the Bering Strait and the adjoining portions of the Bering Sea and Chukchi Sea, deep bummocks and ice keels may leave little vertical room for submarine passage. Widely separated bummocks may be circumnavigated but make for a hazardous passage. Extensive ice areas, with numerous bummocks or ice keels which cross the lane may effectively block both surface and submarine passage into the Arctic Basin.

Bummocks and ice keels may extend downward approximately five times their vertical extent above the ice surface. Therefore, observed ridges of approximately 10 meters may extend as much as 50 meters below sea level. Because of the direct relation of the frequency and vertical extent between these surface features and their subsurface counterparts, aircraft ice reconnaissance should be conducted over a planned submarine cruise track before under ice operations commence.

Skylights are thin places (usually less than 1 meter thick) in the ice canopy, and appear from below as relatively light translucent patches in dark surroundings. The undersurface of a skylight is usually flat; not having been subjected to great pressure. Skylights are called large if big enough for a submarine to attempt to surface through them; that is, have a linear extent of at least 120 meters. Skylights smaller than 120 meters are referred to as small. An ice canopy along a submarine's track that contains a number of large skylights or other features such as leads and polynyas which permit a submarine to surface more frequently than 10 times in 30 miles, is called **friendly ice**. An ice canopy containing no large skylights or other features which permit a submarine to surface is called **hostile ice**.

3414. Great Lakes Ice

Large vessels have been navigating the Great Lakes since the early 1760's. This large expanse of navigable water has since become one of the world's busiest waterways. Due to the northern geographical location of the Great Lakes Basin and its susceptibility to Arctic outbreaks of polar air during winter, the formation of ice plays a major disruptive role in the region's economically vital marine industry. Because of the relatively large size of the five Great Lakes, the ice cover which forms on them is affected by the wind and currents to a greater degree than on smaller lakes. The Great Lakes' northern location results in a long ice growth season, which in combination with the effect of wind and current, imparts to their ice covers some of the characteristics and behavior of an Arctic ice pack.

Since the five Great Lakes extend over a distance of approximately 800 kilometers in a north-south direction, each lake is influenced differently by various meteorological phenomena. These, in combination with the fact that each lake also possesses different geographical characteristics, affect the extent and distribution of their ice covers.

The largest, deepest, and most northern of the Great Lakes is Lake Superior. Initial ice formation normally begins at the end of November or early December in harbors and bays along the north shore, in the western portion of the lake and over the shallow waters of Whitefish Bay. As the season progresses, ice forms and thickens in all coastal areas of the lake perimeter prior to extending offshore. This formation pattern can be attributed to a maximum depth in excess of 400 meters and an associated large heat storage capacity that hinders early ice formation in the center of the lake. During a normal winter, ice not under pressure ranges in thickness from 45–85 centimeters. During severe winters, maximum thicknesses are reported to approach 100 centimeters. Winds and currents acting upon the ice have

been known to cause ridging with heights approaching 10 meters. During normal years, maximum ice cover extends over approximately 75% of the lake surface with heaviest ice conditions occurring by early March. This value increases to 95% coverage during severe winters and decreases to less than 20% coverage during a mild winter. Winter navigation is most difficult in the southeastern portion of the lake due to heavy ridging and compression of the ice under the influence of prevailing westerly winds. Break-up normally starts near the end of March with ice in a state of advanced deterioration by the middle of April. Under normal conditions, most of the lake is ice-free by the first week of May.

Lake Michigan extends in a north-south direction over 490 kilometers and possesses the third largest surface area of the five Great Lakes. Depths range from 280 meters in the center of the lake to 40 meters in the shipping lanes through the Straits of Mackinac, and less in passages between island groups. During average years, ice formation first occurs in the shallows of Green Bay and extends eastward along the northern coastal areas into the Straits of Mackinac during the second half of December and early January. Ice formation and accumulation proceeds southward with coastal ice found throughout the southern perimeter of the lake by late January. Normal ice thicknesses range from 10–20 centimeters in the south to 40–60 centimeters in the north. During normal years, maximum ice cover extends over approximately 40% of the lake surface with heaviest conditions occurring in late February and early March. Ice coverage increases to 85–90% during a severe winter and decreases to only 10–15% during a mild year. Coverage of 100% occurs, but rarely. Throughout the winter, ice formed in mid-lake areas tends to drift eastward because of prevailing westerly winds. This movement of ice causes an area in the southern central portion of the lake to remain ice-free throughout a normal winter. Extensive ridging of ice around the island areas adjacent to the Straits of Mackinac presents the greatest hazard to year-round navigation on this lake. Due to an extensive length and north-south orientation, ice formation and deterioration often occur simultaneously in separate regions of this lake. Ice break-up normally begins by early March in southern areas and progresses to the north by early April. Under normal conditions, only 5–10% of the lake surface is ice covered by mid-April with lingering ice in Green Bay and the Straits of Mackinac completely melting by the end of April.

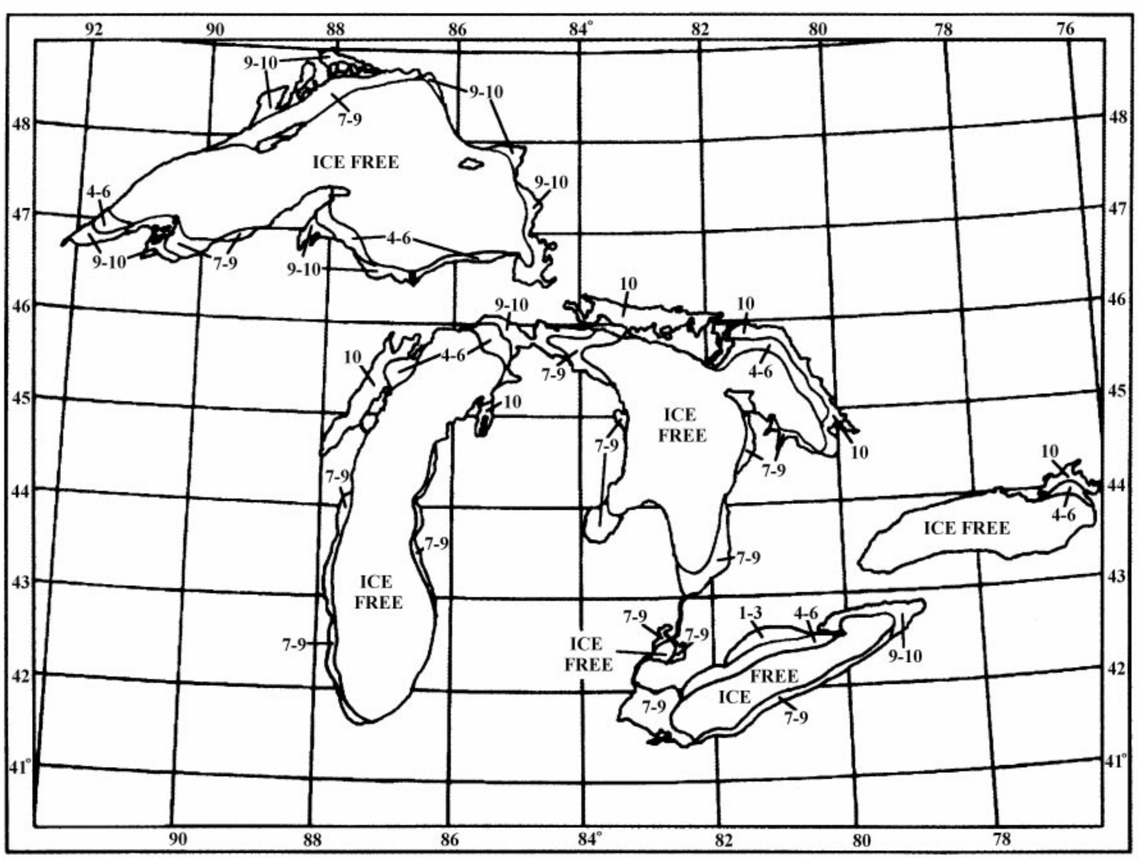


Figure 3414a. Great Lakes maximum ice cover during a mild winter.

Lake Huron, the second largest of the Great Lakes, has maximum depths of 230 and 170 meters in the central basin west of the Bruce peninsula and in Georgian Bay, respectively. The pattern of ice formation in Lake Huron is similar to the north-south progression described in Lake Michigan. Initial ice formation normally begins in the North Channel and along the eastern coast of Saginaw and Georgian Bays by mid-December. Ice rapidly expands into the western and southern coastal areas before extending out into the deeper portions of the lake by late January. Normal ice thicknesses are 45–75 centimeters. During severe winters, maximum ice thicknesses often exceed 100 centimeters with windrows of ridged ice achieving thicknesses of up to 10 meters. During normal years, maximum ice cover occurs in late February with 60% coverage in Lake Huron and nearly 95% coverage in Georgian Bay. These values increase to 85–90% in Lake Huron and nearly 100% in Georgian Bay during severe winters. The percent of lake surface area covered by ice decreases to 20–25% for both bodies of water during mild years. During the winter, ice as a hazard to navigation is of greatest concern in the St. Mary's River/North Channel area and the Straits of Mackinac. Ice break-up normally begins in mid-March in southern coastal areas with melting conditions rapidly spreading northward by early April. A recurring threat to navigation is the southward drift and accumulation of melting ice at the entrance of the St. Clair river. Under normal conditions, the lake becomes ice-free by the first week of May.

The shallowest and most southern of the Great Lakes is Lake Erie. Although the maximum depth nears 65 meters in the eastern portion of the lake, an overall mean depth of only 20 meters results in the rapid accumulation of ice over a short period of time with the onset of winter. Initial ice formation begins in the very shallow western portion of the lake in mid-December with ice rapidly extending eastward by early January. The eastern portion of the lake does not normally become ice covered until late January. During a normal winter, ice thicknesses range from 25–45 centimeters in Lake Erie. During the period of rapid ice growth, prevailing winds and currents routinely move existing ice to the northeastern end of the lake. This accumulation of ice under pressure is often characterized by ridging with maximum heights of 8–10 meters. During a severe winter, initial ice formation may begin in late No-

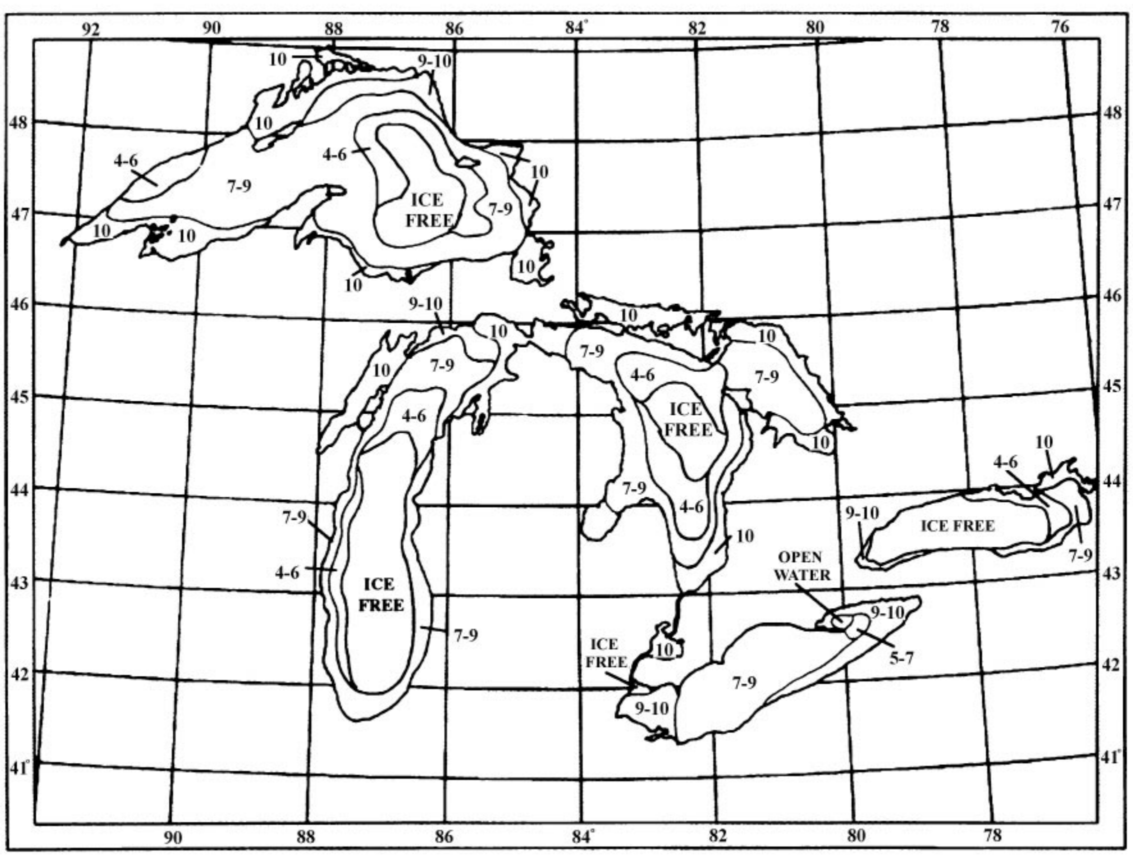


Figure 3414b. Great Lakes maximum ice cover during a normal winter.

vember with maximum seasonal ice thicknesses exceeding 70 centimeters. Since this lake reacts rapidly to changes in air temperature, the variability of percent ice cover is the greatest of the five Great Lakes. During normal years, ice cover extends over approximately 90–95% of the lake surface by mid to late February. This value increases to nearly 100% during a severe winter and decreases to 30% ice coverage during a mild year. Lake St. Clair, on the connecting waterway to Lake Huron, is normally consolidated from the middle of January until early March. Ice break-up normally begins in the western portion of Lake Erie in early March with the lake becoming mostly ice-free by the middle of the month. The exception to this rapid deterioration is the extreme eastern end of the lake where ice often lingers until early May.

Lake Ontario has the smallest surface area and second greatest mean depth of the Great Lakes. Depths range from 245 meters in the southeastern portion of the lake to 55 meters in the approaches to the St. Lawrence River. Like Lake Superior, a large mean depth gives Lake Ontario a large heat storage capacity which, in combination with a small surface area, causes Lake Ontario to respond slowly to changing meteorological conditions. As a result, this lake produces the smallest amount of ice cover found on any of the Great Lakes. Initial ice formation normally begins from the middle to late December in the Bay of Quinte and extends to the western coastal shallows near the mouth of the St. Lawrence River by early January. By the first half of February, Lake Ontario is almost 20% ice covered with shore ice lining the perimeter of the lake. During normal years, ice cover extends over approximately 25% of the lake surface by the second half of February. During this period of maximum ice coverage, ice is typically concentrated in the northeastern portion of the lake by prevailing westerly winds and currents. Ice coverage can extend over 50–60% of the lake surface during a severe winter and less than 10% during a mild year. Level lake ice thicknesses normally fall within the 20–60 centimeter range with occasional reports exceeding 70 centimeters during severe years. Ice break-up normally begins in early March with the lake generally becoming ice-free by mid-April.

The maximum ice cover distribution attained by each of the Great lakes for mild, normal and severe winters is

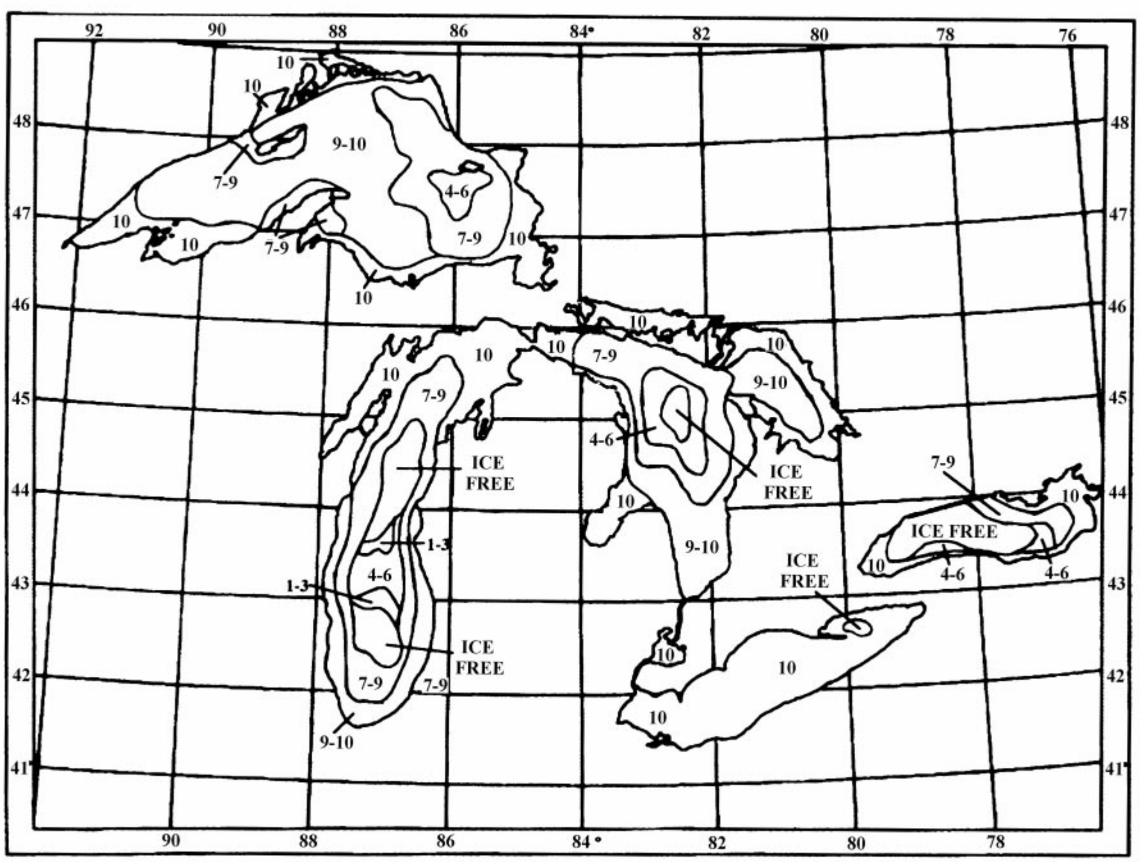


Figure 3414c. Great Lakes maximum ice cover during a severe winter.

shown in Figure 3414a, Figure 3414b and Figure 3414c. It should be noted that although the average maximum ice cover for each lake appears on the same chart, the actual occurrence of each distribution takes place during the time periods described within the preceding narratives.

Information concerning ice analyses and forecasts for the Great Lakes can be obtained from the Director, National Ice Center, 4251 Suitland Road, Washington D.C. 20395 and the National Weather Service Forecast Office located in Cleveland, Ohio. Ice climatological information can be obtained from the Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

ICE INFORMATION SERVICES

3415. Importance Of Ice Information

Advance knowledge of ice conditions to be encountered and how these conditions will change over specified time periods are invaluable for both the planning and operational phases of a voyage to the polar regions. Branches of the United States Federal Government responsible for providing operational ice products and services for safety of navigation include the Departments of Defense (U.S. Navy), Commerce (NOAA), and Transportation (U.S. Coast Guard). Manpower and resources from these agencies comprise the National Ice Center (NIC), which replaced the Navy/NOAA Joint Ice Center. The NIC provides ice products and services to U.S. Government military and civilian interests. Routine and tailored ice products of the NIC shown in Table 3417 can be separated into two categories: a) analyses which describe current ice conditions and b) forecasts which define the expected changes in the existing ice cover over a specified time period.

The content of sea ice analyses is directly dependent upon the planned use of the product, the required level of detail, and the availability of on-site ice observations and/or remotely-sensed data. Ice analyses are produced by blending relatively small numbers of visual ice observations from ships, shore stations and fixed wing aircraft with increasing amounts of remotely sensed data. These data include aircraft and satellite imagery in the visual, infrared, passive microwave and radar bands. The efficient receipt and accurate interpretation of these data are critical to producing a near real-time (24–48 hour old) analysis or “picture” of the ice cover. In general, global and regional scale ice analyses depict ice edge location, ice concentrations within the pack and the ice stages of development or thickness. Local scale ice analyses emphasize the location of thin ice covered or open water leads/polynyas, areas of heavy compression, frequency of ridging, and the presence or absence of dangerous multiyear ice and/or icebergs. The parameters defined in this tactical scale analysis are considered critical to both safety of navigation and the efficient routing of ships through the sea ice cover.

3416. Ice Forecasts And Observations

Sea ice forecasts are routinely separated into four temporal classes: short-term (24–72 hour), weekly (5–7 days), monthly (15–30 days) and seasonal (60–90 days) forecasts. Short-term forecasts are generally paired with local-scale ice analyses and focus on changes in the ice cover based on ice drift, ice formation and ablation, and divergent/convergent processes. Of particular importance are the predicted location of the ice edge and the presence or absence of open water polynyas and coastal/flaw leads. The accurate prediction of the location of these ice features are important for both ice avoidance and ice exploitation purposes.

Similar but with less detail, weekly ice forecasts also emphasize the change in ice edge location and concentration areas within the pack. The National Ice Center presently employs several prediction models to produce both short-term and weekly forecasts. These include empirical models which relate ice drift with geostrophic winds and a coupled dynamic/thermodynamic model called the Polar Ice Prediction System (PIPS). Unlike earlier models, the latter accounts for the effects of ice thickness, concentration, and growth on ice drift.

Monthly ice forecasts predict changes in overall ice extent and are based upon the predicted trends in air temperatures, projected paths of transiting low pressure systems, and continuity of ice conditions.

Seasonal or 90 day ice forecasts predict seasonal ice severity and the projected impact on annual shipping operations. Of particular interest to the National Ice Center are seasonal forecasts for the Alaskan North Slope, Baffin Bay for the annual resupply of Thule, Greenland, and Ross Sea/McMurdo Sound in Antarctica. Seasonal forecasts are also important to Great Lakes and St. Lawrence Seaway shipping interests.

Ice services provided to U.S. Government agencies upon request include aerial reconnaissance for polar shipping operations, ship visits for operational briefing and training, and optimum track ship routing (OTSR) recommendations through ice-infested seas. Commercial operations interested in ice products may obtain routinely produced ice products from the National Ice Center as well as ice analyses and forecasts for Alaskan waters from the National Weather Service Forecast Office in Anchorage, Alaska. Specific information on request procedures, types of ice products, ice services, methods of product dissemination and ship weather support is contained in the publication “Environmental Services for Polar Operations” prepared and distributed by the Director, National Ice Center, 4251 Suitland Road, Washington, D.C., 20395.

The U.S. Coast Guard has an additional responsibility, sep-

arate from the National Ice Center, for providing icebreaker support for polar operations and the administration and operations of the International Ice Patrol (IIP). Inquiries for further information on these subjects should be sent to Commandant (G–N10–3), 2100 Second Street S.W., Washington D.C. 20593.

Other countries which provide sea ice information services are as follows: Arctic – Canada, Denmark (Greenland), Japan (Seas of Okhotsk, Japan and Bo Hai), Iceland, Norway, Russia and the United Kingdom; Antarctic – Argentina, Australia, Chile, Germany, Japan, and Russia; and Baltic – Finland, Germany, Sweden and Russia. Except for the United States, the ice information services of all countries place specific focus upon ice conditions in territorial seas or waters adjacent to claims on the Antarctic continent. The National Ice Center of the United States is the only organization which provides global ice products and services. Names and locations of foreign sea ice service organizations can be found in “Sea Ice Information Services in the World,” WMO Publication No. 574.

Mariners operating in and around sea ice can contribute substantially to increasing the knowledge of synoptic ice conditions, and therefore the accuracy of subsequent ice products by routinely taking and distributing ice observations. The code normally used by personnel trained only to take meteorological observations consists of a five character group appended to the World Meteorological Organization (WMO) weather reporting code: FM 13–X SHIP –Report of Surface Observation from a Sea Station. The five digit ICE group has the following format: ICE + $c_i s_i b_i D_i z_i$. In general, the symbols represent:

c	=	total concentration of sea ice.
s	=	stage of development of sea ice.
b	=	ice of land origin (number of icebergs, growlers and bergy bits).
D	=	bearing of principal ice edge.
z	=	present situation and trend of conditions over three preceding hours.

The complete format and tables for the code are described in the WMO publication “Manual on Codes”, Volume 1, WMO No. 306. This publication is available from the Secretariat of the World Meteorological Organization, Geneva, Switzerland.

A more complete and detailed reporting code (ICEOB) has been in use since 1972 by vessels reporting to the U.S. National Ice Center. 1993 revisions to this code and the procedures for use are described in the “Ice Observation Handbook” prepared and distributed by the Director, National Ice Center, 4251 Suitland Road, Washington D.C., 20395.

All ice observation codes make use of special nomenclature which is precisely defined in several languages by the WMO publication “Sea Ice Nomenclature”, WMO No. 259, TP 145. This publication, available from the Secretariat of the WMO, contains descriptive definitions along with photography of most ice features. This publication is very useful for vessels planning to submit ice observations.

3417. Distribution Of Ice Products And Services

The following is intended as a brief overview of the distribution methods for NIC products and services. For detailed information the user should consult the publications discussed in section 3416 or refer specific inquiries to Director, National Ice Center, 4251 Suitland Road, FOB #4, Room 2301, Washington, D.C. 20395 or call (301) 763–1111 or –2000. Facsimile inquiries can be phoned to (301) 763–1366 and will generally be answered by mail, therefore addresses must be included. NIC ice product distribution methods are as follows:

1. Autopolling: Customer originated menu-driven facsimile product distribution system. Call (301) 763–3190/3191 for menu directions or (301) 763–5972 for assignment of Personal Identification Number (PIN).
2. Autodin: Alphanumeric message transmission to U.S. Government organizations or vessels. Address is NAVICECEN Suitland MD.
3. OMNET/SCIENCENET: electronic mail and bulletin board run by OMNET, Inc. (617) 265–9230. Product request messages may be sent to mailbox NATIONAL.ICE.CTR. Ice products are routinely posted on bulletin board SEA.ICE.
4. INTERNET: Product requests may be forwarded to electronic mail address which is available by request from the NIC at (301) 763–5972.
5. Mail Subscription: For weekly Arctic and Antarctic sea ice analysis charts from the National Climatic Data Center, NESDIS, NOAA, 37 Battery Park Ave., Asheville, NC, 28801–2733. Call (704) 271–4800 with requests for ice products.
6. Mail: Annual ice atlases and multiyear ice climatologies are available either from the National Ice Center (if in stock) or from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA, 22161. Call (703) 487–4600 for sales service desk. Digital files (in SIGRID format) of weekly NIC ice analyses may be obtained from the National Snow and Ice Data Center, CIRES, Box 449, University of Colorado, Boulder, Colorado 80309. Call (303) 492–5171 for information.

NAVAL ICE CENTER PRODUCTS

PRODUCT	*FREQUENCY*	*FORMAT*
GLOBAL SCALE		
Eastern Arctic Analysis/Fcst	Wed	Fax Chart
Western Arctic Analysis/Fcst	Tue	Fax Chart
Antarctic Analysis	Thu	Fax Chart
South Ice Limit-East Arctic	Wed	Posted to OMNET
South Ice Limit-West Arctic	Tue	Posted to OMNET
North Ice Limit-Antarctic	Mon	Fax Chart
30 Day Forecast-East Arctic	1st & 15th of month	Fax Chart
30 Day Forecast-West Arctic	1st & 15th of month	Fax Chart
East Arctic Seasonal Outlook	Annually (15 May)	Booklet
West Arctic Seasonal Outlook	Annually (15 May)	Booklet
REGIONAL SCALE		
Alaska Regional Analysis	Tue & Fri	Fax Chart
Great Lakes Analysis	15 Dec–01 May (Mon, Wed, Fri)	Fax Chart
30 Day Forecast-Gt Lakes	15 Nov–15 Apr (1st & 15th of Mo.)	Fax Chart
St. Mary’s River Analysis	01 Jan– 01 May (Mon, Wed, Fri)	Fax Chart
Ross Sea/McMurdo Sound	Annually	Booklet
Seasonal Outlook	(30 Oct)	Booklet
Gt. Lakes Seasonal Outlook	Annually (1 Dec)	Fax Chart
LOCAL SCALE		
Large-Scale Analysis-User-Defined Area	Thrice Weekly	Fax Chart

Table 3417. Products produced by National Ice Center.

CHAPTER 35

WEATHER ELEMENTS

GENERAL DESCRIPTION OF THE ATMOSPHERE

3500. Introduction

Weather is the state of the earth's atmosphere with respect to temperature, humidity, precipitation, visibility, cloudiness, and other factors. **Climate** refers to the average long-term meteorological conditions of a place or region.

All weather may be traced to the effect of the sun on the earth. Most changes in weather involve large-scale horizontal motion of air. Air in motion is called **wind**. This motion is produced by differences of atmospheric pressure, which are attributable both to differences of temperature and the nature of the motion itself.

Weather is of vital importance to the mariner. The wind and state of the sea affect dead reckoning. Reduced visibility limits piloting. The state of the atmosphere affects electronic navigation and radio communication. If the skies are overcast, celestial observations are not available; and under certain conditions refraction and dip are disturbed. When wind was the primary motive power, knowledge of the areas of favorable winds was of great importance. Modern vessels are still affected considerably by wind and sea.

3501. The Atmosphere

The **atmosphere** is a relatively thin shell of air, water vapor, and suspended particulates surrounding the earth. Air is a mixture gases and, like any gas, is elastic and highly compressible. Although extremely light, it has a definite weight which can be measured. A cubic foot of air at standard sea-level temperature and pressure weighs 1.22 ounces, or about $^{1}/_{817}$th the weight of an equal volume of water. Because of this weight, the atmosphere exerts a pressure upon the surface of the earth of about 15 pounds per square inch.

As altitude increases, air pressure decreases due to the decreased weight of air above. With less pressure, the density decreases. More than three-fourths of the air is concentrated within a layer averaging about 7 statute miles thick, called the **troposphere**. This is the region of most "weather," as the term is commonly understood.

The top of the troposphere is marked by a thin transition zone called the **tropopause**, immediately above which is the **stratosphere**. Beyond this lie several other layers having distinctive characteristics. The average height of the tropopause ranges from about 5 miles or less at high latitudes to about 10 miles at low latitudes.

The **standard atmosphere** is a conventional vertical structure of the atmosphere characterized by a standard sea-level pressure of 1013.25 millibars of mercury (29.92 inches) and a sea-level air temperature of 15° C (59° F). The temperature decreases with height (i.e., **standard lapse rate**) being a uniform 2° C (3.6° F) per thousand feet to 11 kilometers (36,089 feet) and thereafter remains constant at –56.5° C (69.7° F).

Research has indicated that the jet stream is important in relation to the sequence of weather. The **jet stream** refers to relatively strong (≤60 knots) quasi-horizontal winds, usually concentrated within a restricted layer of the atmosphere. There are two commonly known jet streams. The **sub-tropical jet stream (STJ)** occurs in the region of 30°N during the northern hemisphere winter, decreasing in summer. The core of highest winds in the STJ is found at about 12km altitude (40,000 feet) an in the region of 70°W, 40°E, and 150°E, although considerable variability is common. The **polar frontal jet stream (PFJ)** is found in middle to upper-middle latitudes and is discontinuous and variable. Maximum jet stream winds have been measured by weather balloons at 291 knots.

3502. General Circulation Of The Atmosphere

The heat required to warm the air is supplied originally by the sun. As radiant energy from the sun arrives at the earth, about 29 percent is reflected back into space by the earth and its atmosphere, 19 percent is absorbed by the atmosphere, and the remaining 52 percent is absorbed by the surface of the earth. Much of the earth's absorbed heat is radiated back into space. Earth's radiation is in comparatively long waves relative to the short-wave radiation from the sun because it emanates from a cooler body. Long-wave radiation, readily absorbed by the water vapor in the air, is primarily responsible for the warmth of the atmosphere near the earth's surface. Thus, the atmosphere acts much like the glass on the roof of a greenhouse. It allows part of the incoming solar radiation to reach the surface of the earth but is heated by the terrestrial radiation passing outward. Over the entire earth and for long periods of time, the total outgoing energy must be equivalent to the incoming energy (minus any converted to another form and retained), or the temperature of the earth and its atmosphere would steadily increase or decrease. In local areas, or over relatively short periods of time, such a balance is not required, and in fact

does not exist, resulting in changes such as those occurring from one year to another, in different seasons and in different parts of the day.

The more nearly perpendicular the rays of the sun strike the surface of the earth, the more heat energy per unit area is received at that place. Physical measurements show that in the tropics, more heat per unit area is received than is radiated away, and that in polar regions, the opposite is true. Unless there were some process to transfer heat from the tropics to polar regions, the tropics would be much warmer than they are, and the polar regions would be much colder. Atmospheric motions bring about the required transfer of heat. The oceans also participate in the process, but to a lesser degree.

If the earth had a uniform surface and did not rotate on its axis, with the sun following its normal path across the sky (solar heating increasing with decreasing latitude), a simple circulation would result, as shown in Figure 3502a. However, the surface of the earth is far from uniform, being covered with an irregular distribution of land and water. Additionally, the earth rotates about its axis so that the portion heated by the sun continually changes. In addition, the axis of rotation is tilted so that as the earth moves along its orbit about the sun, seasonal changes occur in the exposure of specific areas to the sun's rays, resulting in variations in the heat balance of these areas. These factors, coupled with others, result in constantly changing large-scale movements of air. For example, the rotation of the earth exerts an apparent force, known as Coriolis force, which diverts the air from a direct path between high and low pressure areas. The diversion of the air is toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere. At some distance above the surface of the earth, the wind tends to blow along lines connecting points of equal pressure called **isobars**. The wind is called a **geostrophic wind** if the isobars are straight (great circles) and a **gradient wind** if they are curved. Near the surface of the earth, friction tends to divert the wind from the isobars toward the center of low pressure. At sea, where friction is less than on land, the wind follows the isobars more closely.

A simplified diagram of the general circulation pattern is shown in Figure 3502b. Figure 3502c and Figure 3502d give a generalized picture of the world's pressure distribution and wind systems as actually observed.

A change in pressure with horizontal distance is called a **pressure gradient**. It is maximum along a normal (perpendicular) to the isobars. A force results which is called **pressure gradient force** and is always directed from high to low pressure. Speed of the wind is approximately proportional to this pressure gradient.

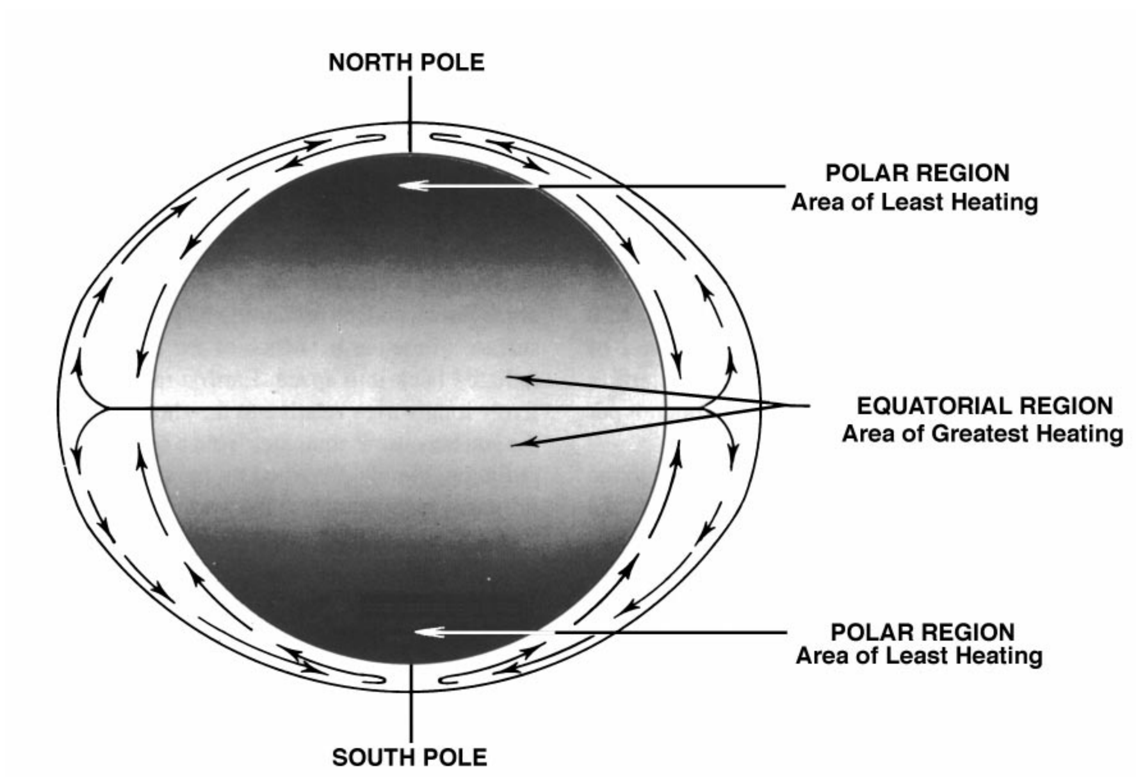


Figure 3502a. Ideal atmospheric circulation for a uniform and nonrotating earth.

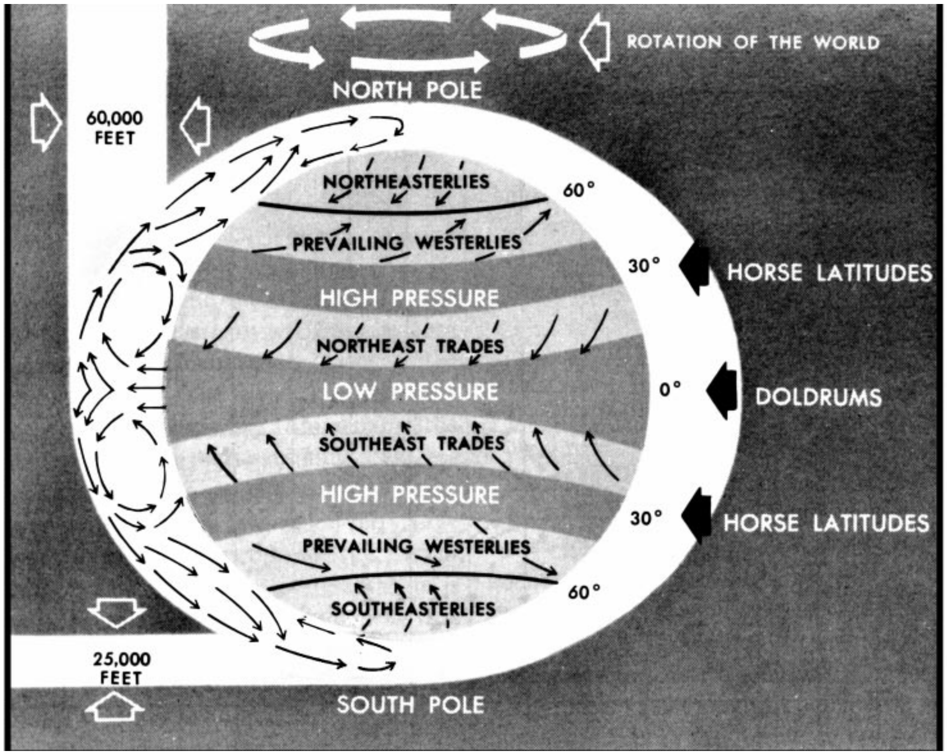


Figure 3502b. Simplified diagram of the general circulation of the atmosphere.

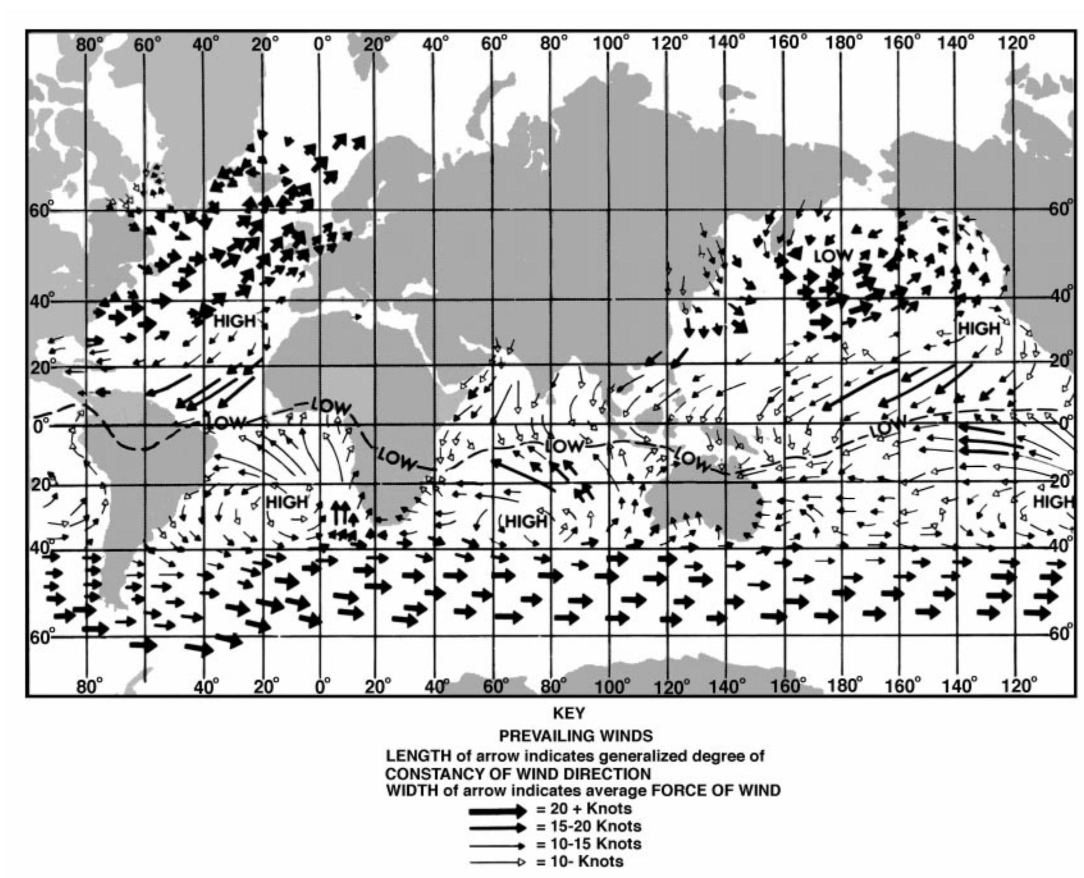


Figure 3502c. Generalized pattern of actual surface winds in January and February.

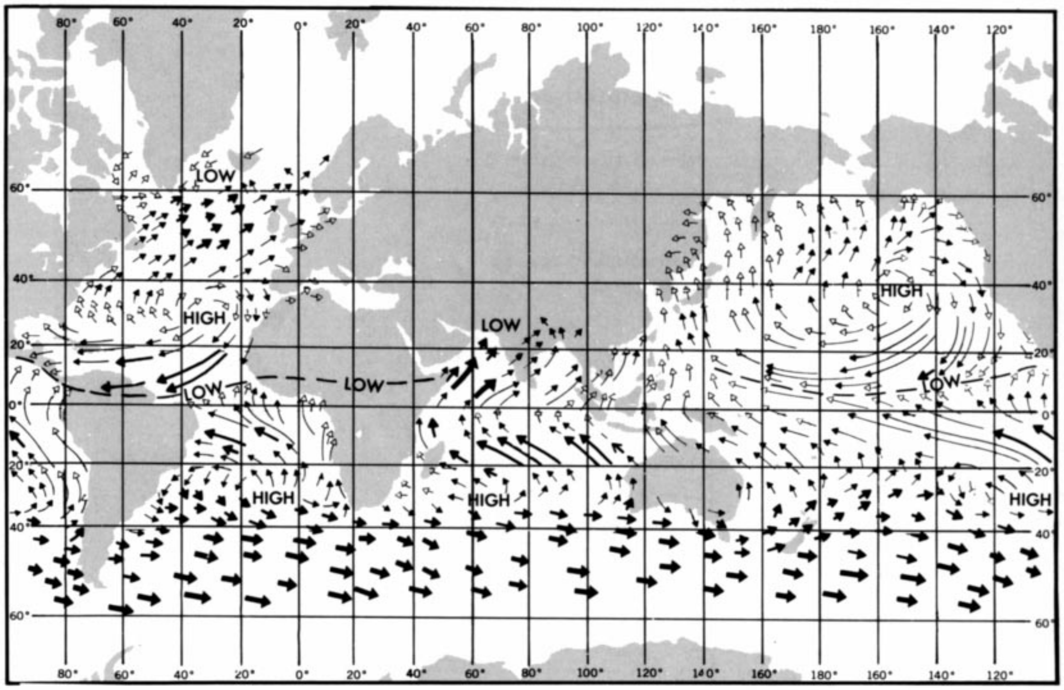


Figure 3502d. Generalized pattern of actual surface winds in July and August. (See key with Figure 3502c.)

MAJOR WIND PATTERNS

3503. The Doldrums

A belt of low pressure at the earth's surface near the equator known as the **doldrums** occupies a position approximately midway between high pressure belts at about latitude 30° to 35° on each side. Except for significant intradiurnal changes, the atmospheric pressure along the equatorial low is almost uniform. With minimal pressure gradient, wind speeds are light and directions are variable. Hot, sultry days are common. The sky is often overcast, and showers and thundershowers are relatively frequent; in these atmospherically unstable areas, brief periods of strong wind occur.

The doldrums occupy a thin belt near the equator, the eastern part in both the Atlantic and Pacific being wider than the western part. However, both the position and extent of the belt vary with longitude and season. During all seasons in the Northern Hemisphere, the belt is centered in the eastern Atlantic and Pacific; however, there are wide excursions of the doldrum regions at longitudes with considerable landmass. On the average, the position is at 5°N, frequently called the **meteorological equator**.

3504. The Trade Winds

The trade winds at the surface blow from the belts of high pressure toward the equatorial belts of low pressure. Because of the rotation of the earth, the moving air is deflected toward the west. Therefore, the trade winds in the Northern Hemisphere are from the northeast and are called the **northeast trades**, while those in the Southern Hemisphere are from the southeast and are called the **southeast trades**. The trade-wind directions are best defined over eastern ocean areas.

The trade winds are generally considered among the most constant of winds, blowing for days or even weeks with little change of direction or speed. However, at times they weaken or shift direction, and there are regions where the general pattern is disrupted. A notable example is found in the island groups of the South Pacific, where the trades are practically nonexistent during January and February. Their best development is attained in the South Atlantic and in the South Indian Ocean. In general, they are stronger during the winter than during the summer season.

In July and August, when the belt of equatorial low pressure moves to a position some distance north of the equator, the southeast trades blow across the equator, into the Northern Hemisphere, where the earth's rotation diverts them toward the right, causing them to be southerly and southwesterly winds. The "southwest monsoons" of the African and Central American coasts originate partly in these diverted southeast trades.

Cyclones from the middle latitudes rarely enter the regions of the trade winds, although tropical cyclones originate within these areas.

3505. The Horse Latitudes

Along the poleward side of each trade-wind belt, and cor-

responding approximately with the belt of high pressure in each hemisphere, is another region with weak pressure gradients and correspondingly light, variable winds. These are called the **horse latitudes**, apparently so named because becalmed sailing ships threw horses overboard in this region when water supplies ran short. The weather is generally good although low clouds are common. Compared to the doldrums, periods of stagnation in the horse latitudes are less persistent. The difference is due primarily to the rising currents of warm air in the equatorial low, which carry large amounts of moisture. This moisture condenses as the air cools at higher levels, while in the horse latitudes the air is apparently descending and becoming less humid as it is warmed at lower heights.

3506. The Prevailing Westerlies

On the poleward side of the high pressure belt in each hemisphere, the atmospheric pressure again diminishes. The currents of air set in motion along these gradients toward the poles are diverted by the earth's rotation toward the east, becoming southwesterly winds in the Northern Hemisphere and northwesterly in the Southern Hemisphere. These two wind systems are known as the **prevailing westerlies** of the temperate zones.

In the Northern Hemisphere this relatively simple pattern is distorted considerably by secondary wind circulations, due primarily to the presence of large landmasses. In the North Atlantic, between latitudes 40° and 50°, winds blow from some direction between south and northwest during 74 percent of the time, being somewhat more persistent in winter than in summer. They are stronger in winter, too, averaging about 25 knots (Beaufort 6) as compared with 14 knots (Beaufort 4) in the summer.

In the Southern Hemisphere the westerlies blow throughout the year with a steadiness approaching that of the trade winds. The speed, though variable, is generally between 17 and 27 knots (Beaufort 5 and 6). Latitudes 40°S to 50°S (or 55°S) where these boisterous winds occur, are called the **roaring forties**. These winds are strongest at about latitude 50°S.

The greater speed and persistence of the westerlies in the Southern Hemisphere are due to the difference in the atmospheric pressure pattern, and its variations, from the Northern Hemisphere. In the comparatively landless Southern Hemisphere, the average yearly atmospheric pressure diminishes much more rapidly on the poleward side of the high pressure belt, and has fewer irregularities due to continental interference, than in the Northern Hemisphere.

3507. Polar Winds

Partly because of the low temperatures near the geographical poles of the earth, the surface pressure tends to remain higher than in surrounding regions, since cold air is more dense than warm air. Consequently, the winds blow outward from the poles, and are deflected westward by the rotation of the earth, to become **northeasterlies** in the Arctic, and **southeasterlies** in the Antarctic. Where the polar easterlies meet the prevailing westerlies, near 50°N and 50°S on the average, a discontinuity in temperature and wind exists. This discontinuity is called the **polar front**. Here the warmer low-latitude air ascends over the colder polar air creating a zone of cloudiness and precipitation.

In the Arctic, the general circulation is greatly modified by surrounding landmasses. Winds over the Arctic Ocean are somewhat variable, and strong surface winds are rarely encountered.

In the Antarctic, on the other hand, a high central landmass is surrounded by water, a condition which augments, rather than diminishes, the general circulation. The high pressure, although weaker than in the horse latitudes, is stronger than in the Arctic, and of great persistence especially in eastern Antarctica. The cold air from the plateau areas moves outward and downward toward the sea and is deflected toward the west by the earth's rotation. The winds remain strong throughout the year, frequently attaining hurricane force near the base of the mountains. These are some of the strongest surface winds encountered anywhere in the world, with the possible exception of those in well-developed tropical cyclones.

3508. Modifications Of The General Circulation

The general circulation of the atmosphere is greatly modified by various conditions.

The high pressure in the horse latitudes is not uniformly distributed around the belts, but tends to be accentuated at several points, as shown in Figure 3502c and Figure 3502d. These semi-permanent highs remain at about the same places with great persistence.

Semi-permanent lows also occur in various places, the most prominent ones being west of Iceland, and over the Aleutians (winter only) in the Northern Hemisphere, and in the Ross Sea and Weddell Sea in the Antarctic areas. The regions occupied by these semi-permanent lows are sometimes called the graveyards of the lows, since many lows move directly into these areas and lose their identity as they merge with and reinforce the semi-permanent lows. The low pressure in these areas is maintained largely by the migratory lows which stall there, with topography also important, especially in Antarctica.

Another modifying influence is land, which undergoes greater temperature changes than does the sea. During the summer, a continent is warmer than its adjacent oceans. Therefore, low pressures tend to prevail over the land. If a climatological belt of high pressure encounters a continent, its pattern is distorted or interrupted, whereas a belt of low pressure is intensified over the same area. In winter, the opposite effect takes place, belts of high pressure being intensified over land and those of low pressure being

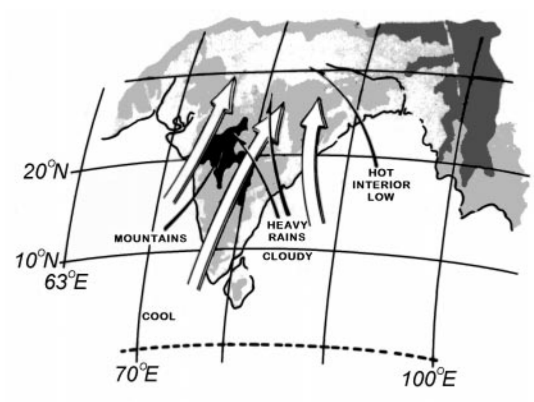


Figure 3508a. The summer monsoon.

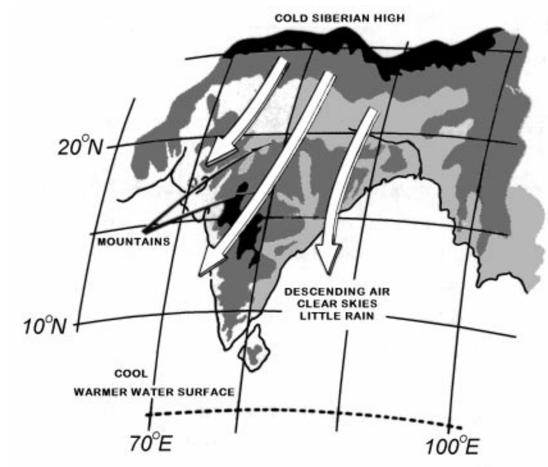


Figure 3508b. The winter monsoon.

weakened.

The most striking example of a wind system produced by the alternate heating and cooling of a landmass is the **monsoon** (seasonal wind) of the China Sea and Indian Ocean. A portion of this effect is shown in Figure 3508a and Figure 3508b. In the summer, low pressure prevails over the warm continent of Asia, and relatively higher pressure prevails over the adjacent sea. Between these two systems the wind blows in a nearly steady direction. The lower portion of the pattern is in the Southern Hemisphere, extending to about 10° south latitude. Here the rotation of the earth causes a deflection to the left, resulting in southeasterly winds. As they cross the equator, the deflection is in the opposite direction, causing them to curve toward the right, becoming southwesterly winds. In the winter, the positions of high and low pressure areas are interchanged, and the direction of flow is reversed.

In the China Sea, the summer monsoon blows from the southwest, usually from May to September. The strong winds are accompanied by heavy squalls and thunderstorms, the rainfall being much heavier than during the winter monsoon. As the season advances, squalls and rain become less frequent. In some places the wind becomes a light breeze which is unsteady in direction, or stops altogether, while in other places it continues almost undiminished, with changes in direction or calms being infrequent. The winter monsoon blows from the northeast, usually from October to April. It blows with a steadiness similar to that of the trade winds, often attaining the speed of a moderate gale (28–33 knots). Skies are generally clear during this season, and there is relatively little rain.

The general circulation is further modified by winds of cyclonic origin and various local winds. Some common local winds are listed by local name below.

Abroholos	A squall frequent from May through August between Cabo de Sao Tome and Cabo Frio on the coast of Brazil.
Bali wind	A strong east wind at the eastern end of Java.
Barat	A heavy northwest squall in Manado Bay on the north coast of the island of Celebes, prevalent from December to February.
Barber	A strong wind carrying damp snow or sleet and spray that freezes upon contact with objects, especially the beard and hair.
Bayamo	A violent wind blowing from the land on the south coast of Cuba, especially near the Bight of Bayamo.
Bentu de Soli	An east wind on the coast of Sardinia.
Bora	A cold, northerly wind blowing from the Hungarian basin into the Adriatic Sea. See also FALL WIND.
Borasco	A thunderstorm or violent squall, especially in the Mediterranean.
Brisa, Briza	1. A northeast wind which blows on the coast of South America or an east wind which blows on Puerto Rico during the trade wind season. 2. The northeast monsoon in the Philippines.
Brisote	The northeast trade wind when it is blowing stronger than usual on Cuba.
Brubu	A name for a squall in the East Indies.
Bull's Eye Squall	A squall forming in fair weather,

Bull's Eye Squall (continued)	characteristic of the ocean off the coast of South Africa. It is named for the peculiar appearance of the small isolated cloud marking the top of the invisible vortex of the storm.
Cape Doctor	The strong southeast wind which blows on the South African coast. Also called the DOCTOR.
Caver, Kaver	A gentle breeze in the Hebrides.
Chubasco	A violent squall with thunder and lightning, encountered during the rainy season along the west coast of Central America.
Churada	A severe rain squall in the Mariana Islands during the northeast monsoon. They occur from November to April or May, especially from January through March.
Cierzo	See MISTRAL.
Contrastes	Winds a short distance apart blowing from opposite quadrants, frequent in the spring and fall in the western Mediterranean.
Cordonazo	The "Lash of St. Francis." Name applied locally to southerly hurricane winds along the west coast of Mexico. It is associated with tropical cyclones in the southeastern North Pacific Ocean. These storms may occur from May to November, but ordinarily affect the coastal areas most severely near or after the Feast of St. Francis, October 4.
Coromell	A night land breeze prevailing from November to May at La Paz, near the southern extremity of the Gulf of California.
Doctor	1. A cooling sea breeze in the Tropics. 2. See HARMATTAN. 3. The strong SE wind which blows on the south African coast. Usually called CAPE DOCTOR.
Elephanta	A strong southerly or southeasterly wind which blows on the Malabar coast of India during the months of September and October and marks the end of the southwest monsoon.
Etesian	A refreshing northerly summer wind of the Mediterranean, especially over the Aegean Sea.
Gregale	A strong northeast wind of the central Mediterranean.
Harmattan	The dry, dusty trade wind blowing off the Sahara Desert across the Gulf of Guinea and the Cape Verde Islands. Sometimes called the DOCTOR, because of its supposed healthful properties.
Knik Wind	A strong southeast wind in the vicinity of Palmer, Alaska, most frequent in the winter.
Kona Storm	A storm over the Hawaiian Islands, characterized by strong southerly or southwesterly winds and heavy rains.
Leste	A hot, dry, easterly wind of the Madeira and Canary Islands.
Levanter	A strong easterly wind of the Mediterranean, especially in the Strait of Gibraltar, attended by cloudy, foggy, and sometimes rainy weather especially in winter.
Levantera	A persistent east wind of the Adriatic, usually accompanied by cloudy weather.
Levanto	A hot southeasterly wind which blows over the Canary Islands.
Leveche	A warm wind in Spain, either a foehn or a hot southerly wind in advance of a low pressure area moving from the Sahara Desert. Called a SIROCCO in other parts of the Mediterranean area.
Maestro	A northwesterly wind with fine weather which blows, especially in summer, in the Adriatic. It is most frequent on the western shore. This wind is also found on the coasts of Corsica and Sardinia.
Matanuska Wind	A strong, gusty, northeast wind which occasionally occurs during the winter in the vicinity of Palmer, Alaska.
Mistral	A cold, dry wind blowing from the north over the northwest coast of the Mediterranean Sea, particularly over the Gulf of Lions. Also called CIERZO. See also FALL WIND.
Nashi, N'aschi	A northeast wind which occurs in winter on the Iranian coast of the Persian Gulf, especially near the entrance to the gulf, and also on the Makran coast. It is probably associated with an outflow from the central Asiatic anticyclone which extends over the high land of Iran. It is similar in character but less severe than the BORA.
Norte	A strong cold northeasterly wind which blows in Mexico and on the shores of the Gulf of Mexico. It results from an outbreak of cold air from the north. It is the Mexican extension of a norther.
Papagayo	A violent northeasterly fall wind on the Pacific coast of Nicaragua and Guatemala. It consists of the cold air mass of a *norte* which has overridden the mountains of Central America. See also TEHUANTEPECER.
Santa Ana	A strong, hot, dry wind blowing out into San Pedro Channel from the southern California desert through Santa Ana Pass.
Shamal	A summer northwesterly wind blowing over Iraq and the Persian Gulf, often strong during the day, but decreasing at night.

Sharki	A southeasterly wind which sometimes blows in the Persian Gulf.
Sirocco	A warm wind of the Mediterranean area, either a foehn or a hot southerly wind in advance of a low pressure area moving from the Sahara or Arabian deserts. Called LEVECHE in Spain.
Squamish	A strong and often violent wind occurring in many of the fjords of British Columbia. Squamishes occur in those fjords oriented in a northeast-southwest or east-west direction where cold polar air can be funneled westward. They are notable in Jervis, Toba, and Bute inlets and in Dean Channel and Portland Canal. Squamishes lose their strength when free of the confining fjords and are not noticeable 15 to 20 miles offshore.
Suestado	A storm with southeast gales, caused by intense cyclonic activity off the coasts of Argentina and Uruguay, which affects the southern part of the coast of Brazil in the winter.
Sumatra	A squall with violent thunder, lightning, and rain, which blows at night in the Malacca Straits, especially during the southwest monsoon. It is intensified by strong mountain breezes.
Taku Wind	A strong, gusty, east-northeast wind, occurring in the vicinity of Juneau, Alaska, between October and March. At the mouth of the Taku River, after which it is named, it sometimes attains hurricane force.
Tehuantepecer	A violent squally wind from north or north-northeast in the Gulf of Tehuantepec (south of southern Mexico) in winter. It originates in the Gulf of Mexico as a norther which crosses the isthmus and blows through the gap between the Mexican and Guatamalan mountains. It may be felt up to 100 miles out to sea. See also PAPAGAYO.
Tramontana	A northeasterly or northerly winter wind off the west coast of Italy. It is a fresh wind of the fine weather mistral type.
Vardar	A cold fall wind blowing from the northwest down the Vardar valley in Greece to the Gulf of Salonica. It occurs when atmospheric pressure over eastern Europe is higher than over the Aegean Sea, as is often the case in winter. Also called VARDARAC.
Warm Braw	A foehn wind in the Schouten Islands north of New Guinea.
White Squall	A sudden, strong gust of wind coming up without warning, noted by whitecaps or white, broken water; usually seen in whirlwind form in clear weather in the tropics.
Williwaw	A sudden blast of wind descending from a mountainous coast to the sea, in the Strait of Magellan or the Aleutian Islands.

AIR MASSES

3509. Types Of Air Masses

Because of large differences in physical characteristics of the earth's surface, particularly the oceanic and continental contrasts, the air overlying these surfaces acquires differing values of temperature and moisture. The processes of radiation and convection in the lower portions of the troposphere act in differing characteristic manners for a number of well-defined regions of the earth. The air overlying these regions acquires characteristics common to the particular area, but contrasting to those of other areas. Each distinctive part of the atmosphere, within which common characteristics prevail over a reasonably large area, is called an **air mass**.

Air masses are named according to their source regions. Four regions are generally recognized: (1) equatorial (E), the doldrums area between the north and south trades; (2) tropical (T), the trade wind and lower temperate regions; (3) polar (P), the higher temperate latitudes; and (4) Arctic or Antarctic (A), the north or south polar regions of ice and snow. This classification is a general indication of relative temperature, as well as latitude of origin.

Air masses are further classified as maritime (m) or continental (c), depending upon whether they form over water or land. This classification is an indication of the relative moisture content of the air mass. Tropical air might be designated maritime tropical (mT) or continental tropical (cT). Similarly, polar air may be either maritime polar (mP) or continental polar (cP). Arctic/Antarctic air, due to the predominance of landmasses and ice fields in the high latitudes, is rarely maritime Arctic (mA). Equatorial air is found exclusively over the ocean surface and is designated neither (cE) nor (mE), but simply (E).

A third classification sometimes applied to tropical and polar air masses indicates whether the air mass is warm (w) or cold (k) relative to the underlying surface. Thus, the symbol mTw indicates maritime tropical air which is warmer than the underlying surface, and cPk indicates continental polar air which is colder than the underlying surface. The w and k classifications are primarily indications of stability

(i.e., change of temperature with increasing height). If the air is cold relative to the surface, the lower portion of the air mass will be heated, resulting in instability (temperature markedly decreases with increasing height) as the warmer air tends to rise by convection. Conversely, if the air is warm relative to the surface, the lower portion of the air mass is cooled, tending to remain close to the surface. This is a stable condition (temperature increases with increasing height).

Two other types of air masses are sometimes recognized. These are monsoon (M), a transitional form between cP and E; and superior (S), a special type formed in the free atmosphere by the sinking and consequent warming of air aloft.

3510. Fronts

As air masses move within the general circulation, they travel from their source regions to other areas dominated by air having different characteristics. This leads to a zone of separation between the two air masses, called a **frontal zone** or **front**, across which temperature, humidity, and wind speed and direction change rapidly. Fronts are represented on weather maps by lines; a cold front is shown with pointed barbs, a warm front with rounded barbs, and an occluded front with both, alternating. A stationary front is shown with pointed and rounded barbs alternating and on opposite sides of the line with the pointed barbs away from the colder air.The front may take on a wave-like character,becoming a "frontal wave."

Before the formation of frontal waves, the isobars (lines of equal atmospheric pressure) tend to run parallel to the fronts. As a wave is formed, the pattern is distorted somewhat, as shown in Figure 3510a. In this illustration, colder air is north of warmer air. In Figures 3510a–3510d isobars are drawn at 4-millibar intervals.

The wave tends to travel in the direction of the general circulation, which in the temperate latitudes is usually in an easterly and slightly poleward direction.

Along the leading edge of the wave, warmer air is replacing colder air. This is called the **warm front**. The trailing edge is the **cold front**, where colder air is underrunning and displacing warmer air.

The warm air, being less dense, tends to ride up greatly over the colder air it is replacing. Partly because of the replacement of cold, dense air with warm, light air, the pressure decreases. Since the slope is gentle, the upper part of a warm frontal surface may be many hundreds of miles ahead of the surface portion. The decreasing pressure, indicated by a "falling barometer," is often an indication of the approach of such a wave. In a slow-moving, well-developed wave, the barometer may begin to fall several days before the wave arrives. Thus, the amount and nature of the change of atmospheric pressure between observations, called pressure tendency, is of assistance in predicting the approach of such a system.

The advancing cold air, being more dense, tends to ride under the warmer air at the cold front, lifting it to greater heights. The slope here is such that the upper-air portion of the cold front is behind the surface position relative to its motion. After a cold front has passed, the pressure increases, giving a rising barometer.

In the first stages, these effects are not marked, but as the wave continues to grow, they become more pronounced, as shown in Figure 3510b. As the amplitude of the wave increases, pressure near the center usually decreases, and the low is said to "deepen." As it deepens, its forward speed generally decreases.

The approach of a well-developed warm front (i.e., when the warm air is mT) is usually heralded not only by falling pressure, but also by a more-or-less regular sequence of clouds. First, cirrus appear. These give way successively to cirrostratus, altostratus, altocumulus, and nimbostratus. Brief showers may precede the steady rain accompanying the nimbostratus.

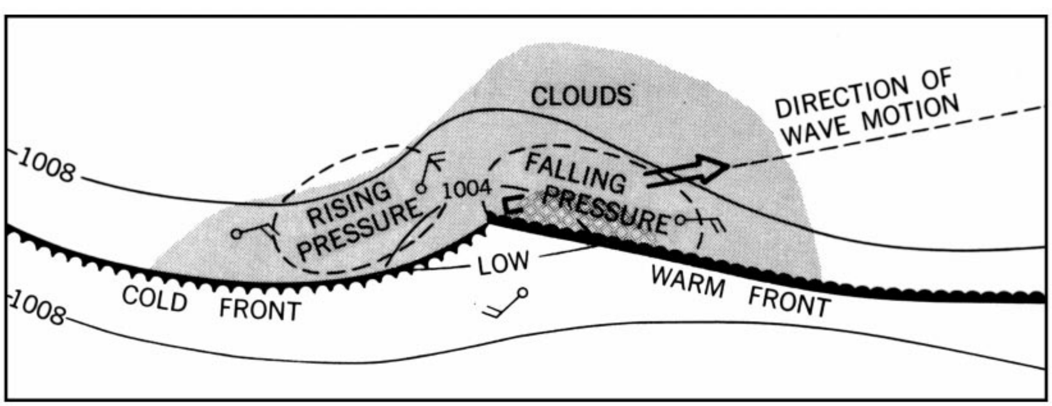


Figure 3510a. First stage in the development of a frontal wave (top view).

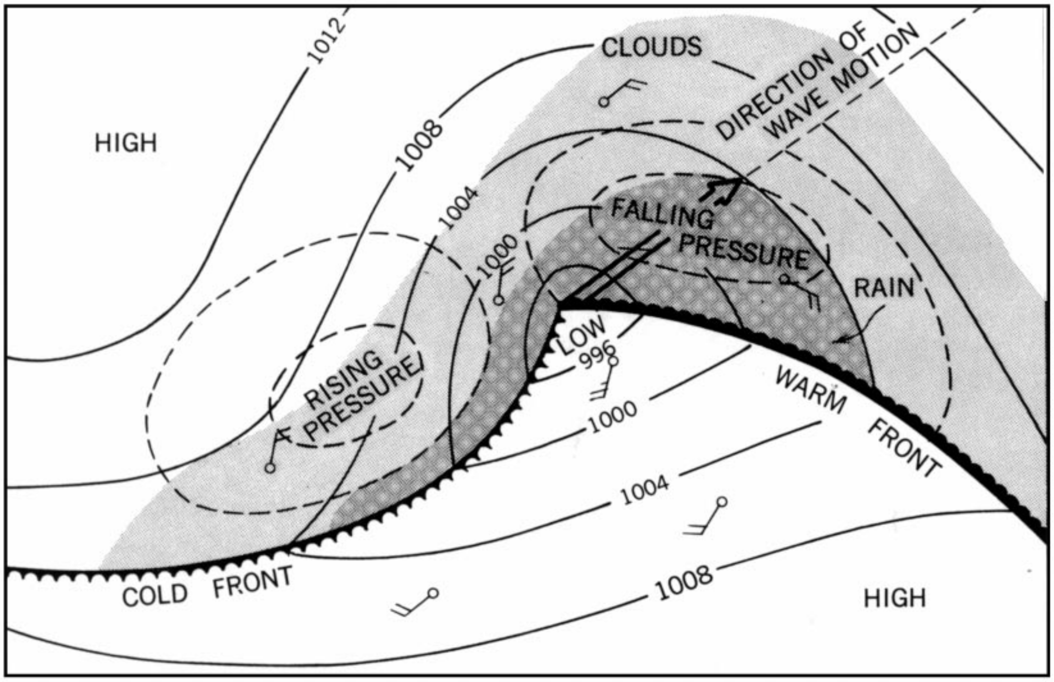


Figure 3510b. A fully developed frontal wave (top view).

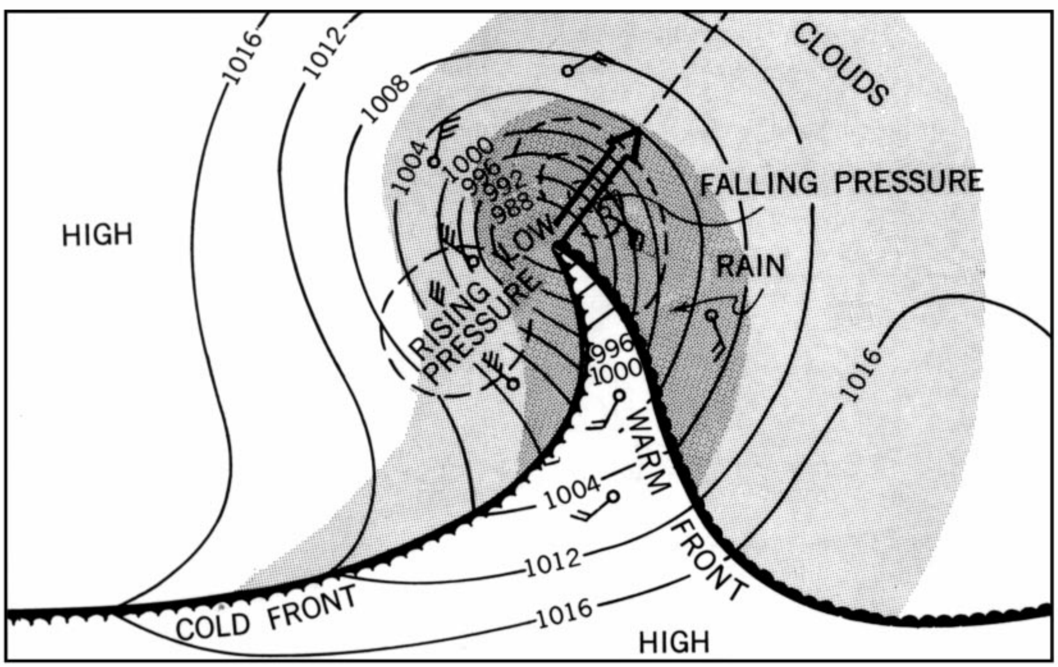


Figure 3510c. A frontal wave nearing occlusion (top view).

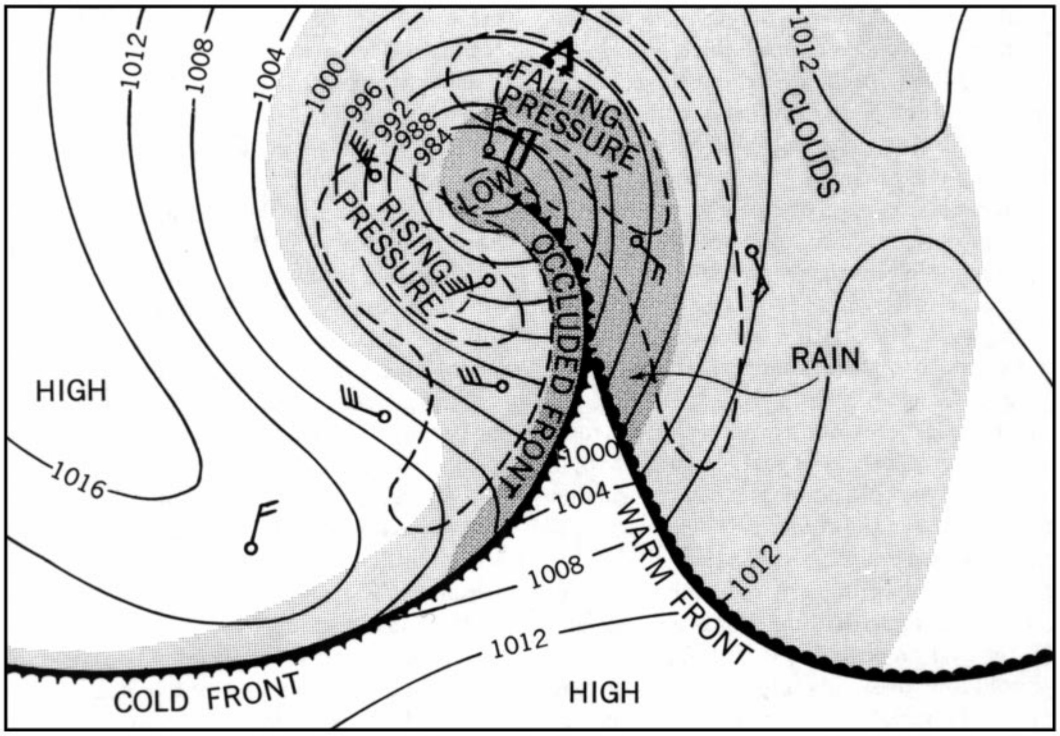


Figure 3510d. An occluded front (top view).

As the warm front passes, the temperature rises, the wind shifts clockwise (in the Northern Hemisphere), and the steady rain stops. Drizzle may fall from low-lying stratus clouds, or there may be fog for some time after the wind shift. During passage of the warm sector between the warm front and the cold front, there is little change in temperature or pressure. However, if the wave is still growing and the low deepening, the pressure might slowly decrease. In the warm sector the skies are generally clear or partly cloudy, with cumulus or stratocumulus clouds most frequent. The warm air is usually moist, and haze or fog may often be present.

As the faster moving, steeper cold front passes, the wind veers (shifts clockwise in the Northern Hemisphere counter-clockwise in the Southern Hemisphere), the temperature falls rapidly, and there are often brief and sometimes violent squalls with showers, frequently accompanied by thunder and lightning. Clouds are usually of the convective type. A cold front usually coincides with a well-defined wind-shift line (a line along which the wind shifts abruptly from southerly or southwesterly to northerly or northwesterly in the Northern Hemisphere, and from northerly or northwesterly to southerly or southwesterly in the Southern Hemisphere). At sea a series of brief showers accompanied by strong, shifting winds may occur along or some distance (up to 200 miles) ahead of a cold front. These are called **squalls** (in common nautical use, the term squall may be additionally

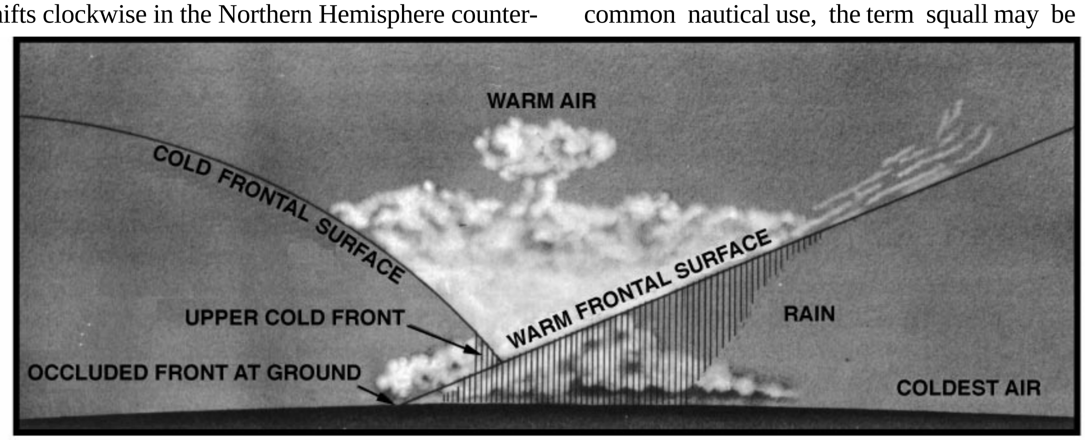


Figure 3510e. An occluded front (cross section).

applied to any severe local storm accompanied by gusty winds, precipitation, thunder, and lightning), and the line along which they occur is called a **squall line**.

Because of its greater speed and steeper slope, which may approach or even exceed the vertical near the earth's surface (due to friction), a cold front and its associated weather pass more quickly than a warm front. After a cold front passes, the pressure rises, often quite rapidly, the visibility usually improves, and the clouds tend to diminish. Clear, cool or cold air replaces the warm hazy air.

As the wave progresses and the cold front approaches the slower moving warm front, the low becomes deeper and the warm sector becomes smaller, as shown in Figure 3510c.

Finally, the faster moving cold front overtakes the warm front (Figure 3510d), resulting in an **occluded front** at the surface, and an upper front aloft (Figure 3510e). When the two parts of the cold air mass meet, the warmer portion tends to rise above the colder part. The warm air continues to rise until the entire frontal system dissipates. As the warmer air is replaced by colder air, the pressure gradually rises, a process called **filling**. This usually occurs within a few days after an occluded front forms. Finally, there results a cold low, or simply a low pressure system across which little or no gradient in temperature and moisture can be found.

The sequence of weather associated with a low depends greatly upon the observer's location with respect to the path of the center. That described above assumes that the low center passes poleward of the observer. If the low center passes south of the observer, between the observer and the equator, the abrupt weather changes associated with the passage of fronts are not experienced. Instead, the change from the weather characteristically found ahead of a warm front, to that behind a cold front, takes place gradually, the exact sequence dictated by distance from the center, and the severity and age of the low.

Although each low generally follows this pattern, no two are ever exactly alike. Other centers of low pressure and high pressure, and the air masses associated with them, even though they may be 1,000 miles or more away, influence the formation and motion of individual low centers and their accompanying weather. Particularly, a high stalls or diverts a low. This is true of temporary highs as well as semi-permanent highs, but not to as great a degree.

3511. Cyclones And Anticyclones

An area of relatively low pressure, generally circular, is called a **cyclone**. Its counterpart for high pressure is called an **anticyclone**. These terms are used particularly in connection with the winds associated with such centers. Wind tends to blow from an area of high pressure to one of low pressure, but due to rotation of the earth, wind is deflected toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere.

Because of the rotation of the earth, therefore, the circulation tends to be counterclockwise around areas of low pressure and clockwise around areas of high pressure in the Northern Hemisphere, and the speed is proportional to the spacing of isobars. In the Southern Hemisphere, the direction of circulation is reversed. Based upon this condition, a general rule, known as Buys Ballot's Law, or the Baric Wind Law, can be stated:

If an observer in the Northern Hemisphere faces away from the surface wind, the low pressure is toward his left; the high pressure is toward his right.

If an observer in the Southern Hemisphere faces away from the surface wind, the low pressure is toward his right; the high pressure is toward his left.

In a general way, these relationships apply in the case of the general distribution of pressure, as well as to temporary local pressure systems.

The reason for the wind shift along a front is that the isobars have an abrupt change of direction along these lines. Since the direction of the wind is directly related to the direction of isobars, any change in the latter results in a shift in the wind direction.

In the Northern Hemisphere, the wind shifts toward the right (clockwise) when either a warm or cold front passes. In the Southern Hemisphere, the shift is toward the left (counterclockwise). When an observer is on the poleward side of the path of a frontal wave, wind shifts are reversed (i.e., to the left in the Northern Hemisphere and to the right in the Southern Hemisphere).

In an anticyclone, successive isobars are relatively far apart, resulting in light winds. In a cyclone, the isobars are more closely spaced. With a steeper pressure gradient, the winds are stronger.

Since an anticyclonic area is a region of outflowing winds, air is drawn into it from aloft. Descending air is warmed, and as air becomes warmer, its capacity for holding uncondensed moisture increases. Therefore, clouds tend to dissipate. Clear skies are characteristic of an anticyclone, although scattered clouds and showers are sometimes encountered.

In contrast, a cyclonic area is one of converging winds. The resulting upward movement of air results in cooling, a condition favorable to the formation of clouds and precipitation. More or less continuous rain and generally stormy weather are usually associated with a cyclone.

Between the two hemispheric belts of high pressure associated with the horse latitudes, called subtropical anticyclones, cyclones form only occasionally over certain areas at sea, generally in summer and fall. Tropical cyclones (hurricanes and typhoons) are usually quite violent.

In the areas of the prevailing westerlies in temperate latitudes, migratory cyclones (lows) and anticyclones (highs) are a common occurrence. These are sometimes called extratropical cyclones and extratropical anticyclones to distinguish them from the more violent tropical cyclones. Formation occurs over sea and land. The lows intensify as they move poleward; the highs weaken as they move equatorward. In their early stages, cyclones are elongated, as shown in Figure 3510a, but as their life cycle proceeds, they become more nearly circular (Figure 3510b, Figure 3510c, and Figure 3510d).

LOCAL WEATHER PHENOMENA

3512. Local Winds

In addition to the winds of the general circulation and those associated with migratory cyclones and anticyclones, there are numerous local winds which influence the weather in various places.

The most common are the land and sea breezes, caused by alternate heating and cooling of land adjacent to water. The effect is similar to that which causes the monsoons, but on a much smaller scale, and over shorter periods. By day the land is warmer than the water, and by night it is cooler. This effect occurs along many coasts during the summer. Between about 0900 and 1100 local time the temperature of the land becomes greater than that of the adjacent water. The lower levels of air over the land are warmed, and the air rises, drawing in cooler air from the sea. This is the **sea breeze**. Late in the afternoon, when the sun is low in the sky, the temperature of the two surfaces equalizes and the breeze stops. After sunset, as the land cools below the sea temperature, the air above it is also cooled. The contracting cool air becomes more dense, increasing the pressure near the surface. This results in an outflow of winds to the sea. This is the **land breeze**, which blows during the night and dies away near sunrise. Since the atmospheric pressure changes associated with this cycle are not great, the accompanying winds generally do not exceed gentle to moderate breezes. The circulation is usually of limited extent, reaching a distance of perhaps 20 miles inland, and not more than 5 or 6 miles offshore, and to a height of a few hundred feet. In the doldrums and subtropics, this process is repeated with great regularity throughout most of the year. As the latitude increases, it becomes less prominent, being masked by winds of migratory cyclones and anticyclones. However, the effect often may be present to reinforce, retard, or deflect stronger prevailing winds.

Varying conditions of topography produce a large variety of local winds throughout the world. Winds tend to follow valleys, and to be deflected from high banks and shores. In mountain areas wind flows in response to temperature distribution and gravity. An **anabolic wind** is one that blows up an incline, usually as a result of surface heating. A **katabatic wind** is one which blows down an incline. There are two types, foehn and fall wind.

The foehn (fãn) is a warm dry wind which initiates from horizontally moving air encountering a mountain barrier. As it blows upward to clear the mountains, it is cooled below the dew point, resulting in clouds and rain on the windward side. As the air continues to rise, its rate of cooling is reduced because the condensing water vapor gives off heat to the surrounding atmosphere. After crossing the mountain barrier, the air flows downward along the leeward slope, being warmed by compression as it descends to lower levels. Since it loses less heat on the ascent than it gains during descent, and since it has lost its moisture during ascent, it arrives at the bottom of the mountains as very warm, dry air. This accounts for the warm, arid regions along the eastern side of the Rocky Mountains and in similar areas. In the Rocky Mountain region this wind is known by the name **chinook**. It may occur at any season of the year, at any hour of the day or night, and have any speed from a gentle breeze to a gale. It may last for several days, or for a very short period. Its effect is most marked in winter, when it may cause the temperature to rise as much as 20°F to 30°F within 15 minutes, and cause snow and ice to melt within a few hours. On the west coast of the United States, a foehn wind, given the name **Santa Ana**, blows through a pass and down a valley of that name in Southern California. This wind is frequently very strong and may endanger small craft immediately off the coast.

A cold wind blowing down an incline is called a **fall wind**. Although it is warmed somewhat during descent, as is the foehn, it remains cold relative to the surrounding air. It occurs when cold air is dammed up in great quantity on the windward side of a mountain and then spills over suddenly, usually as an overwhelming surge down the other side. It is usually quite violent, sometimes reaching hurricane force. A different name for this type wind is given at each place where it is common. The **tehuantepecer** of the Mexican and Central American coast, the **pampero** of the Argentine coast, the **mistral** of the western Mediterranean, and the **bora** of the eastern Mediterranean are examples of this wind.

Many other local winds common to certain areas have been given distinctive names.

A **blizzard** is a violent, intensely cold wind laden with snow mostly or entirely picked up from the ground, although the term is often used popularly to refer to any heavy snowfall accompanied by strong wind. A **dust whirl** is a rotating column of air about 100 to 300 feet in height, carrying dust, leaves, and other light material. This wind, which is similar to a waterspout at sea, is given various local names such as dust devil in southwestern United States and desert devil in South Africa. A **gust** is a sudden, brief increase in wind speed, followed by a slackening, or the violent wind or squall that accompanies a thunderstorm. A puff of wind or a light breeze affecting a small area, such as would cause patches of ripples on the surface of water, is called a **cat's paw**.

3513. Waterspouts

A **waterspout** is a small, whirling storm over ocean or inland waters. Its chief characteristic is a funnel-shaped cloud; when fully developed it extends from the surface of the water to the base of a cumulus cloud. The water in a waterspout is mostly confined to its lower portion, and may

Figure 3513. Waterspouts.

be either salt spray drawn up by the sea surface, or freshwater resulting from condensation due to the lowered pressure in the center of the vortex creating the spout. The air in waterspouts may rotate clockwise or counterclockwise, depending on the manner of formation. They are found most frequently in tropical regions, but are not uncommon in higher latitudes.

There are two types of waterspouts: those derived from violent convective storms over land moving seaward, called tornadoes, and those formed over the sea and which are associated with fair or foul weather. The latter type is most common, lasts a maximum of 1 hour, and has variable strength. Many waterspouts are no stronger than dust whirlwinds, which they resemble; at other times they are strong enough to destroy small craft or to cause damage to larger vessels, although modern ocean-going vessels have little to fear.

Waterspouts vary in diameter from a few feet to several hundred feet, and in height from a few hundred feet to several thousand feet. Sometimes they assume fantastic shapes; in early stages of development an hour glass shape between cloud and sea is common. Since a waterspout is often inclined to the vertical, its actual length may be much greater than indicated by its height.

3514. Deck Ice

Ships traveling through regions where the air temperature is below freezing may acquire thick deposits of ice as a result of salt spray freezing on the rigging, deckhouses, and deck areas. This accumulation of ice is called **ice accretion**. Also, precipitation may freeze to the superstructure and exposed areas of the vessel, increasing the load of ice.

On small vessels in heavy seas and freezing weather, deck ice may accumulate very rapidly and increase the topside weight enough to capsize the vessel. Fishing vessels with outriggers, A-frames, and other top hamper are particularly susceptible.

Figure 3514. Deck ice.

RESTRICTED VISIBILITY

3515. Fog

Fog is a cloud whose base is at the surface of the earth. Fog is composed of droplets of water or ice crystals (ice fog) formed by condensation or crystallization of water vapor in the air.

Radiation fog forms over low-lying land on clear, calm nights. As the land radiates heat and becomes cooler, it cools the air immediately above the surface. This causes a temperature inversion to form, the temperature increasing with height. If the air is cooled to its dew point, fog forms. Often, cooler and more dense air drains down surrounding slopes to heighten the effect. Radiation fog is often quite shallow, and is usually densest at the surface. After sunrise the fog may “lift” and gradually dissipate, usually being entirely gone by noon. At sea the temperature of the water undergoes little change between day and night, and so radiation fog is seldom encountered more than 10 miles from shore.

Advection fog forms when warm, moist air blows over a colder surface and is cooled below its dew point. It is most commonly encountered at sea, may be quite dense, and often persists over relatively long periods. Advection fog is common over cold ocean currents. If the wind is strong enough to thoroughly mix the air, condensation may take place at some distance above the surface of the earth, forming low stratus clouds rather than fog.

Off the coast of California, seasonal winds create an offshore current which displaces the warm surface water, causing an upwelling of colder water. Moist Pacific air is transported along the coast in the same wind system, and is cooled by the relatively cold water. Advection fog results. In the coastal valleys, fog is sometimes formed when moist air blown inland during the afternoon is cooled by radiation during the night.

When very cold air moves over warmer water, wisps of visible water vapor may rise from the surface as the water

"steams," In extreme cases this **frost smoke**, or **Arctic sea smoke**, may rise to a height of several hundred feet, the portion near the surface constituting a dense fog which obscures the horizon and surface objects, but usually leaves the sky relatively clear.

Haze consists of fine dust or salt particles in the air, too small to be individually apparent, but in sufficient number to reduce horizontal visibility and cast a bluish or yellowish veil over the landscape, subduing its colors and making objects appear indistinct. This is sometimes called **dry haze** to distinguish it from **damp haze**, which consists of small water droplets or moist particles in the air, smaller and more scattered than light fog. In international meteorological practice, the term "haze" is used to refer to a condition of atmospheric obscurity caused by dust and smoke.

Mist is synonymous with drizzle in the United States but is often considered as intermediate between haze and fog in its properties. Heavy mist can reduce visibility to a mile or less.

A mixture of smoke and fog is called **smog**. Normally it is not a problem in navigation except in severe cases accompanied by an offshore wind from the source, when it may reduce visibility to 2–4 miles.

ATMOSPHERIC EFFECTS ON LIGHT RAYS

3516. Mirage

Light is refracted as it passes through the atmosphere. When refraction is normal, objects appear slightly elevated, and the visible horizon is farther from the observer than it otherwise would be. Since the effects are uniformly progressive, they are not apparent to the observer. When refraction is not normal, some form of mirage may occur. A **mirage** is an optical phenomenon in which objects appear distorted, displaced (raised or lowered), magnified, multiplied, or inverted due to varying atmospheric refraction which occurs when a layer of air near the earth's surface differs greatly in density from surrounding air. This may occur when there is a rapid and sometimes irregular change of temperature or humidity with height.

If there is a temperature inversion (increase of temperature with height), particularly if accompanied by a rapid decrease in humidity, the refraction is greater than normal. Objects appear elevated, and the visible horizon is farther away. Objects which are normally below the horizon become visible. This is called **looming**. If the upper portion of an object is raised much more than the bottom part, the object appears taller than usual, an effect called **towering**. If the lower part of an object is raised more than the upper part, the object appears shorter, an effect called **stooping**. When the refraction is greater than normal, a **superior mirage** may occur. An inverted image is seen above the object, and sometimes an erect image appears over the inverted one, with the bases of the two images touching. Greater than normal refraction usually occurs when the water is much colder than the air above it.

If the temperature decrease with height is much greater than normal, refraction is less than normal, or may even cause bending in the opposite direction. Objects appear lower than normal, and the visible horizon is closer to the observer. This is called **sinking**. Towering or stooping may occur if conditions are suitable. When the refraction is reversed, an **inferior mirage** may occur. A ship or an island appears to be floating in the air above a shimmering horizon, possibly with an inverted image beneath it. Conditions suitable to the formation of an inferior mirage occur when the surface is much warmer than the air above it. This usually requires a heated landmass, and therefore is more common near the coast than at sea.

When refraction is not uniformly progressive, objects may appear distorted, taking an almost endless variety of shapes. The sun when near the horizon is one of the objects most noticeably affected. A **fata morgana** is a complex mirage characterized by marked distortion, generally in the vertical. It may cause objects to appear towering, magnified, and at times even multiplied.

3517. Sky Coloring

White light is composed of light of all colors. Color is related to wavelength, the visible spectrum varying from about 0.000038 to 0.000076 centimeters. The characteristics of each color are related to its wavelength (or frequency). The shorter the wavelength, the greater the amount of bending when light is refracted. It is this principle that permits the separation of light from celestial bodies into a **spectrum** ranging from red, through orange, yellow, green, and blue, to violet, with long-wave **infrared** being slightly outside the visible range at one end and short-wave **ultraviolet** being slightly outside the visible range at the other end. Light of shorter wavelength is scattered and diffracted more than that of longer wavelength.

Light from the sun and moon is white, containing all colors. As it enters the earth's atmosphere, a certain amount of it is scattered. The blue and violet, being of shorter wavelength than other colors, are scattered most. Most of the violet light is absorbed in the atmosphere. Thus, the scattered blue light is most apparent, and the sky appears blue. At great heights, above most of the atmosphere, it appears black.

When the sun is near the horizon, its light passes through more of the atmosphere than when higher in the sky, resulting in greater scattering and absorption of blue and green light, so that a larger percentage of the red and orange light penetrates to the observer. For this reason the sun and moon appear redder at this time, and when this light

falls upon clouds, they appear colored. This accounts for the colors at sunset and sunrise. As the setting sun approaches the horizon, the sunset colors first appear as faint tints of yellow and orange. As the sun continues to set, the colors deepen. Contrasts occur, due principally to difference in height of clouds. As the sun sets, the clouds become a deeper red, first the lower clouds and then the higher ones, and finally they fade to a gray.

When there is a large quantity of smoke, dust, or other material in the sky, unusual effects may be observed. If the material in the atmosphere is of suitable substance and quantity to absorb the longer wave red, orange, and yellow radiation, the sky may have a greenish tint, and even the sun or moon may appear green. If the green light, too, is absorbed, the sun or moon may appear blue. A green moon or blue moon is most likely to occur when the sun is slightly below the horizon and the longer wavelength light from the sun is absorbed, resulting in green or blue light being cast upon the atmosphere in front of the moon. The effect is most apparent if the moon is on the same side of the sky as the sun.

3518. Rainbows

The **rainbow**, that familiar arc of concentric colored bands seen when the sun shines on rain, mist, spray, etc., is caused by refraction, internal reflection, and diffraction of sunlight by the drops of water. The center of the arc is a point 180° from the sun, in the direction of a line from the sun, through the observer. The radius of the brightest rainbow is 42°. The colors are visible because of the difference in the amount of refraction of the different colors making up white light, the light being spread out to form a spectrum. Red is on the outer side and blue and violet on the inner side, with orange, yellow, and green between, in that order from red.

Sometimes a secondary rainbow is seen outside the primary one, at a radius of about 50°. The order of colors of this rainbow is reversed. On rare occasions a faint rainbow is seen on the same side as the sun. The radius of this rainbow and the order of colors are the same as those of the primary rainbow.

A similar arc formed by light from the moon (a lunar rainbow) is called a **moonbow**. The colors are usually very faint. A faint, white arc of about 39° radius is occasionally seen in fog opposite the sun. This is called a **fogbow**, although its origin is controversial, some considering it a halo.

3519. Halos

Refraction, or a combination of refraction and reflection, of light by ice crystals in the atmosphere may cause a **halo** to appear. The most common form is a ring of light of radius 22° or 46° with the sun or moon at the center. Cirrostratus clouds are a common source of atmospheric ice crystals. Occasionally a faint, white circle with a radius of 90° appears around the sun. This is called a **Hevelian halo**. It is probably caused by refraction and internal reflection of the sun's light by bipyramidal ice crystals. A halo formed by refraction is usually faintly colored like a rainbow, with red nearest the celestial body, and blue farthest from it.

A brilliant rainbow-colored arc of about a quarter of a circle with its center at the zenith, and the bottom of the arc about 46° above the sun, is called a **circumzenithal arc**. Red is on the outside of the arc, nearest the sun. It is produced by the refraction and dispersion of the sun's light striking the top of prismatic ice crystals in the atmosphere. It usually lasts for only about 5 minutes, but may be so brilliant as to be mistaken for an unusually bright rainbow. A similar arc formed 46° below the sun, with red on the upper side, is called a **circumhorizontal arc**. Any arc tangent to a heliocentric halo (one surrounding the sun) is called a **tangent arc**. As the sun increases in elevation, such arcs tangent to the halo of 22° gradually bend their ends toward each other. If they meet, the elongated curve enclosing the circular halo is called a **circumscribed halo**. The inner edge is red.

A halo consisting of a faint, white circle through the sun and parallel to the horizon is called a **parhelic circle**. A similar one through the moon is called a **paraselenic circle**. They are produced by reflection of sunlight or moonlight from vertical faces of ice crystals.

A **parhelion (plural: parhelia)** is a form of halo consisting of an image of the sun at the same altitude and some distance from it, usually 22°, but occasionally 46°. A similar phenomenon occurring at an angular distance of 120° (sometimes 90° or 140°) from the sun is called a **paranthelion**. One at an angular distance of 180°, a rare occurrence, is called an **anthelion**, although this term is also used to refer to a luminous, colored ring or glory sometimes seen around the shadow of one's head on a cloud or fog bank. A parhelion is popularly called a **mock sun** or **sun dog**. Similar phenomena in relation to the moon are called **paraselene** (popularly a **mock moon** or **moon dog**), **parantiselene**, and **antiselene**. The term parhelion should not be confused with perihelion, the orbital point nearest the sun when the sun is the center of attraction.

A **sun pillar** is a glittering shaft of white or reddish light occasionally seen extending above and below the sun, usually when the sun is near the horizon. A phenomenon similar to a sun pillar, but observed in connection with the moon, is called a **moon pillar**. A rare form of halo in which horizontal and vertical shafts of light intersect at the sun is called a **sun cross**. It is probably due to the simultaneous occurrence of a sun pillar and a parhelic circle.

3520. Corona

When the sun or moon is seen through altostratus clouds, its outline is indistinct, and it appears surrounded by a glow of light called a **corona**. This is somewhat similar in appearance to the corona seen around the sun during a solar eclipse. When the effect is due to clouds, however, the glow may be accompanied by one or more rainbow-colored rings

of small radii, with the celestial body at the center. These can be distinguished from a halo by their much smaller radii and also by the fact that the order of the colors is reversed, red being on the inside, nearest the body, in the case of the halo, and on the outside, away from the body, in the case of the corona.

A corona is caused by diffraction of light by tiny droplets of water. The radius of a corona is inversely proportional to the size of the water droplets. A large corona indicates small droplets. If a corona decreases in size, the water droplets are becoming larger and the air more humid. This may be an indication of an approaching rainstorm. The glow portion of a corona is called an **aureole**.

3521. The Green Flash

As light from the sun passes through the atmosphere, it is refracted. Since the amount of bending is slightly different for each color, separate images of the sun are formed in each color of the spectrum. The effect is similar to that of imperfect color printing, in which the various colors are slightly out of register. However, the difference is so slight that the effect is not usually noticeable. At the horizon, where refraction is maximum, the greatest difference, which occurs between violet at one end of the spectrum and red at the other, is about 10 seconds of arc. At latitudes of the United States, about 0.7 second of time is needed for the sun to change altitude by this amount when it is near the horizon. The red image, being bent least by refraction, is first to set and last to rise. The shorter wave blue and violet colors are scattered most by the atmosphere, giving it its characteristic blue color. Thus, as the sun sets, the green image may be the last of the colored images to drop out of sight. If the red, orange, and yellow images are below the horizon, and the blue and violet light is scattered and absorbed, the upper rim of the green image is the only part seen, and the sun appears green. This is the **green flash**. The shade of green varies, and occasionally the blue image is seen, either separately or following the green flash (at sunset). On rare occasions the violet image is also seen. These colors may also be seen at sunrise, but in reverse order. They are occasionally seen when the sun disappears behind a cloud or other obstruction.

The phenomenon is not observed at each sunrise or sunset, but under suitable conditions is far more common than generally supposed. Conditions favorable to observation of the green flash are a sharp horizon, clear atmosphere, a temperature inversion, and a very attentive observer. Since these conditions are more frequently met when the horizon is formed by the sea than by land, the phenomenon is more common at sea. With a sharp sea horizon and clear atmosphere, an attentive observer may see the green flash at as many as 50 percent of sunsets and sunrises, although a telescope may be needed for some of the observations.

Duration of the green flash (including the time of blue and violet flashes) of as long as 10 seconds has been reported, but such length is rare. Usually it lasts for a period of about $^1/_2$ to 2 $^1/_2$ seconds, with about 1 $^1/_4$ seconds being average. This variability is probably due primarily to changes in the index of refraction of the air near the horizon.

Under favorable conditions, a momentary green flash has been observed at the setting of Venus and Jupiter. A telescope improves the chances of seeing such a flash from a planet, but is not a necessity.

3522. Crepuscular Rays

Crepuscular rays are beams of light from the sun passing through openings in the clouds, and made visible by illumination of dust in the atmosphere along their paths. Actually, the rays are virtually parallel, but because of perspective, appear to diverge. Those appearing to extend downward are popularly called **backstays of the sun**, or the sun drawing water. Those extending upward and across the sky, appearing to converge toward a point 180° from the sun, are called **anticrepuscular rays**.

THE ATMOSPHERE AND RADIO WAVES

3523. Atmospheric Electricity

Radio waves traveling through the atmosphere exhibit many of the properties of light, being refracted, reflected, diffracted, and scattered. These effects are discussed in greater detail in Chapter 10, Radio Waves in Navigation.

Various conditions induce the formation of electrical charges in the atmosphere. When this occurs, there is often a difference of electron charge between various parts of the atmosphere, and between the atmosphere and earth or terrestrial objects. When this difference exceeds a certain minimum value, depending upon the conditions, the static electricity is discharged, resulting in phenomena such as lightning or St. Elmo’s fire.

Lightning is the discharge of electricity from one part of a thundercloud to another, between different clouds, or between a cloud and the earth or a terrestrial object.

Enormous electrical stresses build up within thunderclouds, and between such clouds and the earth. At some point the resistance of the intervening air is overcome. At first the process is a progressive one, probably starting as a brush discharge (St. Elmo’s fire), and growing by ionization. The breakdown follows an irregular path along the line of least resistance. A hundred or more individual discharges may be necessary to complete the path between points of opposite polarity. When this “leader stroke” reaches its destination, a heavy “main stroke” immediately follows in the opposite direction. This main stroke is the visible lightning, which may

be tinted any color, depending upon the nature of the gases through which it passes. The illumination is due to the high degree of ionization of the air, which causes many of the atoms to become excited and emit radiation.

Thunder, the noise that accompanies lightning, is caused by the heating and ionizing of the air by lightning, which results in rapid expansion of the air along its path and the sending out of a compression wave. Thunder may be heard at a distance of as much as 15 miles, but generally does not carry that far. The elapsed time between the flash of lightning and reception of the accompanying sound of thunder is an indication of the distance, because of the difference in travel time of light and sound. Since the former is comparatively instantaneous, and the speed of sound is about 1,117 feet per second, the approximate distance in nautical miles is equal to the elapsed time in seconds, divided by 5.5. If the thunder accompanying lightning cannot be heard due to its distance, the lightning is called **heat lightning**.

St. Elmo's fire is a luminous discharge of electricity from pointed objects such as the masts and antennas of ships, lightning rods, steeples, mountain tops, blades of grass, human hair, arms, etc., when there is a considerable difference in the electrical charge between the object and the air. It appears most frequently during a storm. An object from which St. Elmo's fire emanates is in danger of being struck by lightning, since this discharge may be the initial phase of the leader stroke. Throughout history those who have not understood St. Elmo's fire have regarded it with superstitious awe, considering it a supernatural manifestation. This view is reflected in the name **corposant** (from "corpo santo," meaning "body of a saint") sometimes given this phenomenon.

The **aurora** is a luminous glow appearing in varied forms in the thin atmosphere high above the earth in high latitudes. It closely follows solar flare activity, and is believed caused by the excitation of atoms of oxygen and hydrogen, and molecules of nitrogen (N_2). Auroras extend across hundreds of kilometers of sky, in colored sheets, folds, and rays, constantly changing in form and color. On occasion they are seen in temperate or even more southern latitudes. The maximum occurrence is at about 64–70° of geomagnetic latitude. These are called the **auroral zones** in both northern and southern regions.

The aurora of the northern regions is the **Aurora Borealis** or **northern lights**, and that of the southern region the **Aurora Australis**, or **southern lights**. The term **polar lights** is occasionally used to refer to either.

In the northern zone, there is an apparent horizontal motion to the westward in the evening and eastward in the morning; a general southward motion occurs during the course of the night.

Variation in auroral activity occurs in sequence with the 11-year sunspot cycle, and also with the 27-day period of the sun's synodical rotation. Daily occurrence is greatest near midnight.

WEATHER ANALYSIS AND FORECASTING

3524. Forecasting Weather

The prediction of weather at some future time is based upon an understanding of weather processes, and observations of present conditions. Thus, when there is a certain sequence of cloud types, rain usually can be expected to follow. If the sky is cloudless, more heat will be received from the sun by day, and more heat will be radiated outward from the warm earth by night than if the sky is overcast. If the wind is from a direction that transports warm, moist air over a colder surface, fog can be expected. A falling barometer indicates the approach of a "low," probably accompanied by stormy weather. Thus, before meteorology passed from an "art" to "science," many individuals learned to interpret certain atmospheric phenomena in terms of future weather, and to make reasonably accurate forecasts for short periods into the future.

With the establishment of weather observation stations, continuous and accurate weather information became available. As observations expanded and communication techniques improved, knowledge of simultaneous conditions over wider areas became available. This made possible the collection of "synoptic" reports at civilian and military forecast centers.

Individual observations are made at stations on shore and aboard vessels at sea. Observations aboard merchant ships at sea are made and transmitted on a voluntary and cooperative basis. The various national meteorological services supply shipmasters with blank forms, printed instructions, and other materials essential to the making, recording, and interpreting of observations. Any shipmaster can render a particularly valuable service by reporting all unusual or non-normal weather occurrences.

Symbols and numbers are used to indicate on a synoptic chart, popularly called a weather map, the conditions at each observation station. Isobars are drawn through lines of equal atmospheric pressure, fronts are located and symbolically marked (See Figure 3525), areas of precipitation and fog are indicated, etc.

Ordinarily, weather maps for surface observations are prepared every 6 (sometimes 3) hours. In addition, synoptic charts for selected heights are prepared every 12 (sometimes 6) hours. Knowledge of conditions aloft is of value in establishing the three-dimensional structure and motion of the atmosphere as input to the forecast.

With the advent of the digital computer, highly sophisticated numerical models have been developed to analyze and forecast weather patterns. The civil and military weath-

er centers prepare and disseminate vast numbers of weather charts (analyses and prognoses) daily to assist local forecasters in their efforts to provide users with accurate weather forecasts. The accuracy of forecast decreases with the length of the forecast period. A 12-hour forecast is likely to be more reliable than a 24-hour forecast. Long term forecasts for 2 weeks or a month in advance are limited to general statements. For example, a prediction may be made about which areas will have temperatures above or below normal, and how precipitation will compare with normal, but no attempt is made to state that rainfall will occur at a certain time and place.

Forecasts are issued for various areas. The national meteorological services of most maritime nations, including the United States, issue forecasts for ocean areas and warnings of approaching storms. The efforts of the various nations are coordinated through the World Meteorological Organization.

3525. Weather Forecast Dissemination

Dissemination of weather information is carried out in a number of ways. Forecasts are widely broadcast by commercial and government radio stations and printed in newspapers. Shipping authorities on land are kept informed by telegraph and telephone. Visual storm warnings are displayed in various ports, and storm warnings are broadcast by radio.

Through the use of codes, a simplified version of synoptic weather charts is transmitted to various stations ashore and afloat. Rapid transmission of completed maps is accomplished by facsimile. This system is based upon detailed scanning, by a photoelectric detector, of illuminated black and white copy. The varying degrees of light intensity are converted to electric energy, which is transmitted to the receiver and converted back to a black and white presentation. The proliferation of both commercial and restricted computer bulletin board systems having weather information has also greatly increased the accessibility of environmental data.

Complete information on dissemination of weather information by radio is provided in *Selected Worldwide Marine Weather Broadcasts*, published jointly by the National Weather Service and the Naval Meteorology and

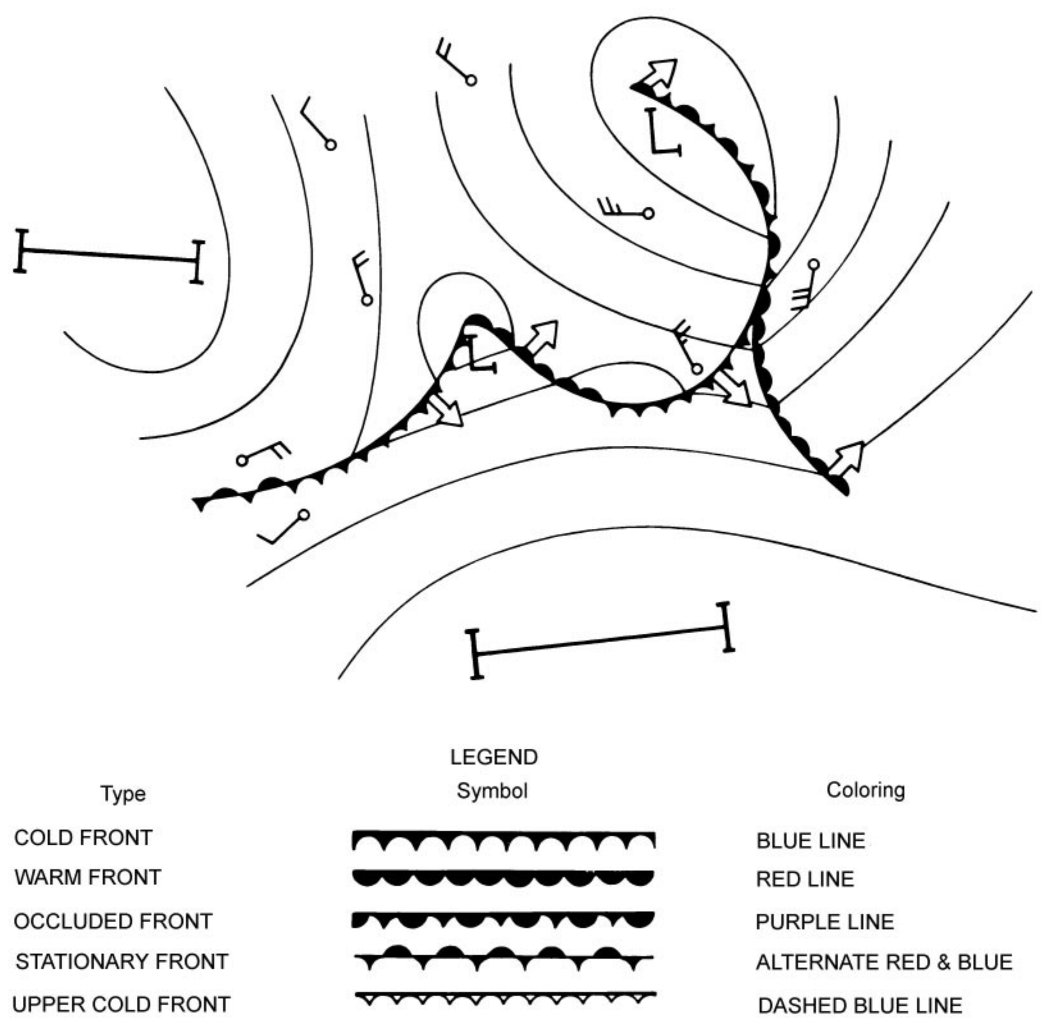


Figure 3525. Designation of fronts on weather maps.

Oceanography Command. This publication lists broadcast schedules and weather codes. Information on day and night visual storm warnings is given in the various volumes of Sailing Directions (Enroute), and (Planning Guide).

3526. Interpreting Weather

The factors which determine weather are numerous and varied. Ever-increasing knowledge regarding them makes possible a continually improving weather service. However, the ability to forecast is acquired through study and long practice, and therefore the services of a trained meteorologist should be utilized whenever available.

The value of a forecast is increased if one has access to the information upon which it is based, and understands the principles and processes involved. It is sometimes as important to know the various types of weather which may be experienced as it is to know which of several possibilities is most likely to occur.

At sea, reporting stations are unevenly distributed, sometimes leaving relatively large areas with incomplete reports, or none at all. Under these conditions, the locations of highs, lows, fronts, etc., are imperfectly known, and their very existence may even be in doubt. At such times the mariner who can interpret the observations made from his own vessel may be able to predict weather for the next several hours more reliably than a trained meteorologist ashore.

CHAPTER 36

TROPICAL CYCLONES

CAUSES AND DESCRIPTION OF TROPICAL CYCLONES

3600. Introduction

A **tropical cyclone** is a cyclone originating in the tropics or subtropics. Although it generally resembles the extratropical cyclone of higher latitudes, there are important differences, the principal one being the concentration of a large amount of energy into a relatively small area. Tropical cyclones are infrequent in comparison with middle and high latitude storms, but they have a record of destruction far exceeding that of any other type of storm. Because of their fury, and because they are predominantly oceanic, they merit special attention by mariners.

A tropical storm has a deceptively small size, and beautiful weather may be experienced only a few hundred miles from the center. The rapidity with which the weather can deteriorate with approach of the storm, and the violence of the fully developed tropical cyclone, are difficult to imagine if they have not been experienced.

On his second voyage to the New World, Columbus encountered a tropical storm. Although his vessels suffered no damage, this experience proved valuable during his fourth voyage when his ships were threatened by a fully developed hurricane. Columbus read the signs of an approaching storm from the appearance of a southeasterly swell, the direction of the high cirrus clouds, and the hazy appearance of the atmosphere. He directed his vessels to shelter. The commander of another group, who did not heed the signs, lost most of his ships and more than 500 men perished.

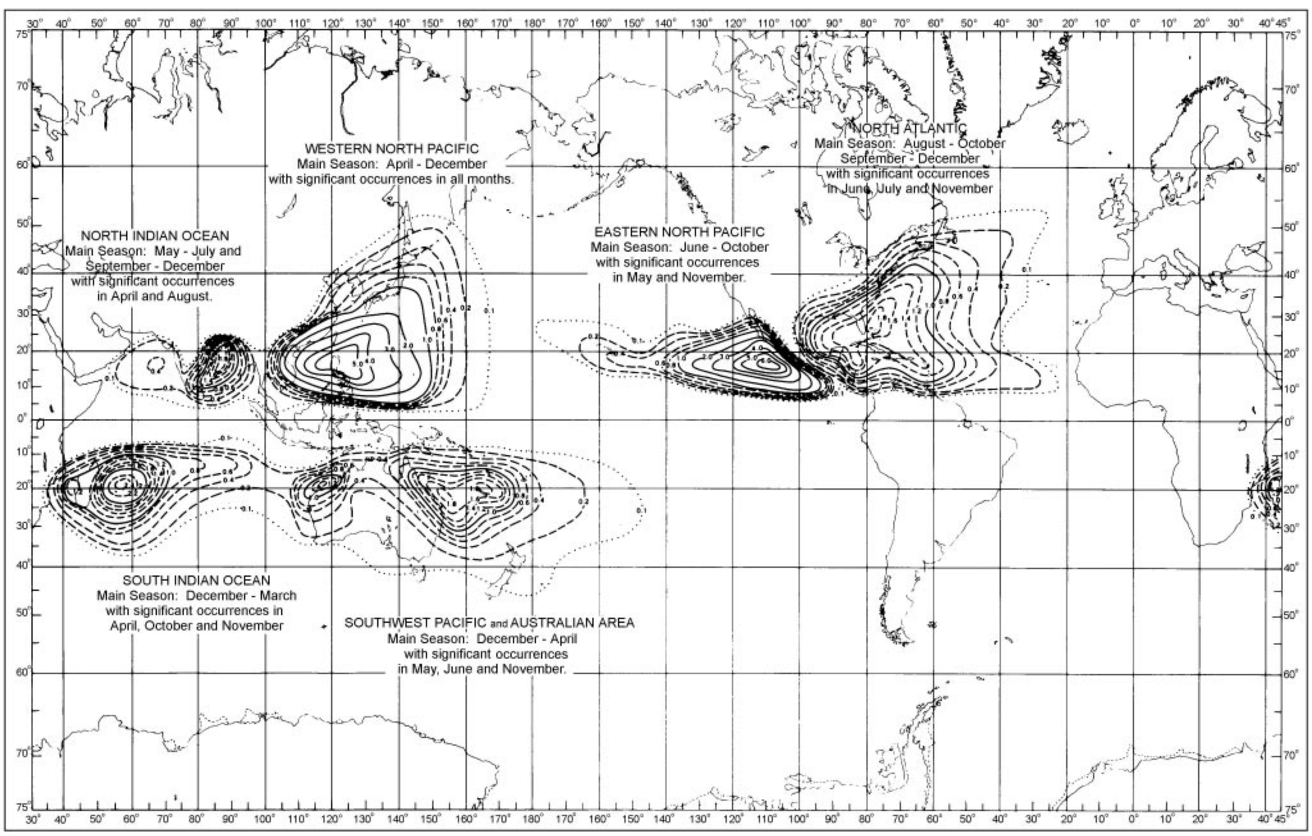


Figure 3602. Areas in which tropical cyclones occur. The average number of tropical cyclones per 5˚ square has been analyzed for this figure. The main season for intense tropical storm activity is also shown for each major basin.

3601. Definitions

"Tropical cyclone" is the term for cyclones originating in the tropics or subtropics. These cyclones are classified by form and intensity as they increase in size.

A **tropical disturbance** is a discrete system of apparently organized convection, generally 100 to 300 miles in diameter, having a nonfrontal migratory character, and having maintained its identity for 24 hours or more. It may or may not be associated with a detectable disturbance of the wind field. It has no strong winds and no closed isobars i.e., isobars that completely enclose the low.

At its next stage of development it becomes a **tropical depression**. A tropical depression has one or more closed isobars and some rotary circulation at the surface. The highest sustained (1-minute mean) surface wind speed is 33 knots.

The next stage is **tropical storm**. A tropical storm has closed isobars and a distinct rotary circulation. The highest sustained (1-minute mean) surface wind speed is 34 to 63 knots.

When fully developed, a **hurricane** or **typhoon** has closed isobars, a strong and very pronounced rotary circulation, and a sustained (1-minute mean) surface wind speed of 64 knots or higher.

3602. Areas Of Occurrence

Tropical cyclones occur almost entirely in six distinct areas, four in the Northern Hemisphere and two in the Southern Hemisphere as shown in Figure 3602. The name by which the tropical cyclone is commonly known varies somewhat with the locality.

1. North Atlantic. A tropical cyclone with winds of 64 knots or greater is called a **hurricane**.
2. Eastern North Pacific. The name **hurricane** is used as in the North Atlantic.
3. Western North Pacific. A fully developed storm with winds of 64 knots or greater is called a **typhoon** or, locally in the Philippines, a **baguio**.
4. North Indian Ocean. A tropical cyclone with winds of 34 knots or greater is called a **cyclonic storm**.
5. South Indian Ocean. A tropical cyclone with winds of 34 knots or greater is called a **cyclone**.
6. Southwest Pacific and Australian Area. The name **cyclone** is used as in the South Indian Ocean. A severe tropical cyclone originating in the Timor Sea and moving southwest and then southeast across the interior of northwestern Australia is called a **willy-willy**.

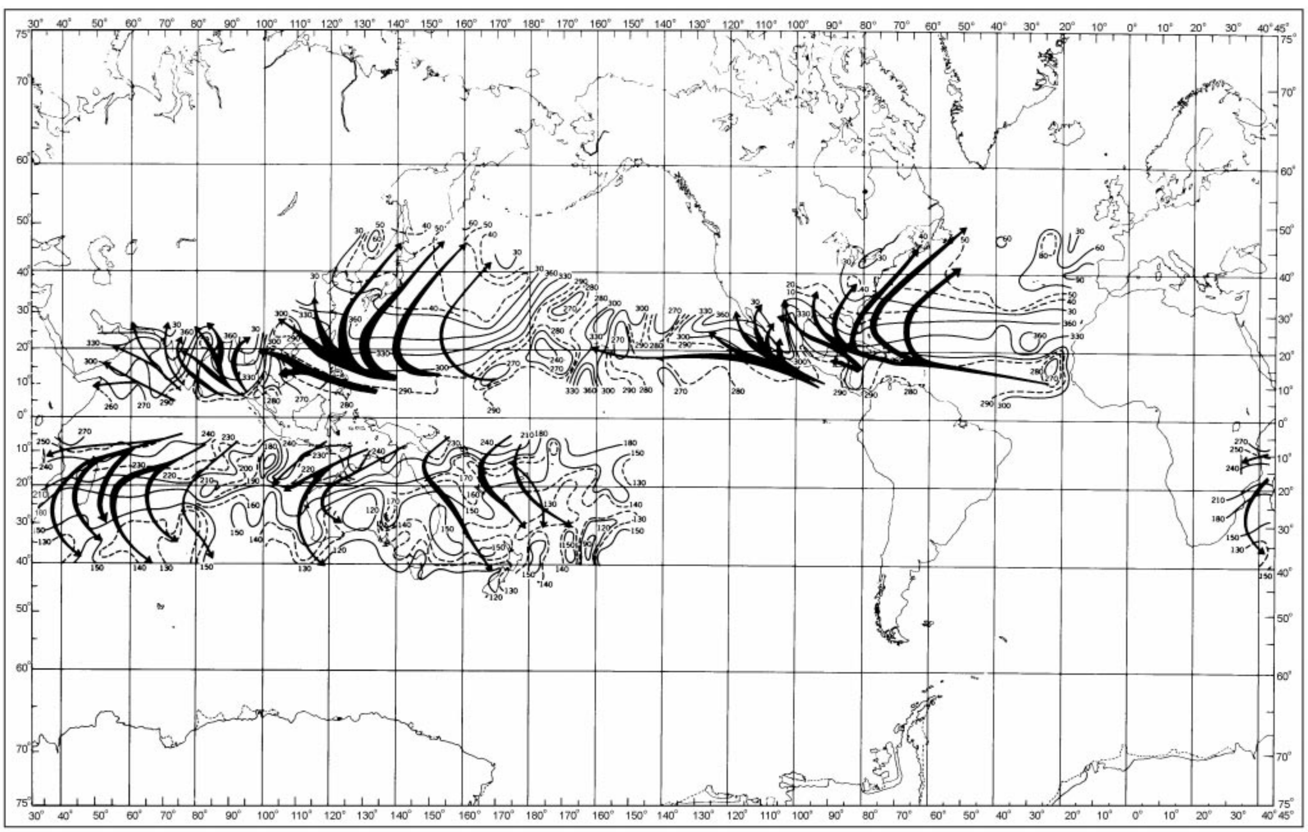


Figure 3603a. Storm tracks.The width of the arrow indicates the approximate frequency of storms; the wider the arrow the higher the frequency. Isolines on the base map show the resultant direction toward which storms moved. Data for the entire year has been summarized for this figure.

Tropical cyclones have not been observed in the South Atlantic or in the South Pacific east of 140°W.

3603. Origin, Season And Frequency

See Figures 3603a and 3603b. Origin, season, and frequency of occurrence of the tropical cyclones in the six areas are as follows:

North Atlantic: Tropical cyclones can affect the entire North Atlantic Ocean in any month. However, they are mostly a threat south of about 35°N from June through November; August, September, and October are the months of highest incidence. See Figure 3603b. About 9 or 10 tropical cyclones (tropical storms and hurricanes) form each season; 5 or 6 reach hurricane intensity (winds of 64 knots and higher). A few hurricanes have generated winds estimated as high as 200 knots. Early and late season storms usually develop west of 50°W; during August and September, this spawning ground extends to the Cape Verde Islands. These storms usually move westward or west northwestward at speeds of less than 15 knots in the lower latitudes. After moving into the northern Caribbean or Greater Antilles regions, they usually either move toward the Gulf of Mexico or recurve and accelerate in the North Atlantic. Some will recurve after reaching the Gulf of Mexico, while others will continue westward to a landfall in Texas or Mexico.

Eastern North Pacific: The season is from June through October, although a storm can form in any month. An average of 15 tropical cyclones form each year with about 6 reaching hurricane strength. The most intense storms are often the early- and late-season ones; these form close to the coast and far south. Mid season storms form anywhere in a wide band from the Mexican-Central American coast to the Hawaiian Islands. August and September are the months of highest incidence. These storms differ from their North Atlantic counterparts in that they are usually smaller in size. However, they can be just as intense.

Western North Pacific: More tropical cyclones form in the tropical western North Pacific than anywhere else in the world. More than 25 tropical storms develop each year, and about 18 become typhoons. These typhoons are the largest and most intense tropical cyclones in the world. Each year an average of five generate maximum winds over 130 knots; circulations covering more than 600 miles in diameter are not uncommon. Most of these storms form east

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
NORTH ATLANTIC													
TROPICAL STORMS	*	*	*	*	0.1	0.4	0.3	1.0	1.5	1.2	0.4	*	4.2
HURRICANES	*	*	*	*	*	0.3	0.4	1.5	2.7	1.3	0.3	*	5.2
TROPICAL STORMS AND HURRICANES	*	*	*	*	*0.2*	*0.7*	*0.8*	*2.5*	*4.3*	*2.5*	*0.7*	*0.1*	*9.4*

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
EASTERN NORTH PACIFIC													
TROPICAL STORMS	*	*	*	*	*	1.5	2.8	2.3	2.3	1.2	0.3	*	9.3
HURRICANES	*	*	*	*	0.3	0.6	0.9	2.0	1.8	1.0	*	*	5.8
TROPICAL STORMS AND HURRICANES	*	*	*	*	*0.3*	*2.0*	*3.6*	*4.5*	*4.1*	*2.2*	*0.3*	*	*15.2*

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
WESTERN NORTH PACIFIC													
TROPICAL STORMS	0.2	0.3	0.3	0.2	0.4	0.5	1.2	1.8	1.5	1.0	0.8	0.6	7.5
TYPHOONS	0.3	0.2	0.2	0.7	0.9	1.2	2.7	4.0	4.1	3.3	2.1	0.7	17.8
TROPICAL STORMS AND TYPHOONS	*0.4*	*0.4*	*0.5*	*0.9*	*1.3*	*1.8*	*3.9*	*5.8*	*5.6*	*4.3*	*2.9*	*1.3*	*25.3*

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
SOUTHWEST PACIFIC AND AUSTRALIAN AREA													
TROPICAL STORMS	2.7	2.8	2.4	1.3	0.3	0.2	*	*	*	0.1	0.4	1.5	10.9
HURRICANES	0.7	1.1	1.3	0.3	*	*	0.1	0.1	*	*	0.3	0.5	3.8
TROPICAL STORMS AND HURRICANES	*3.4*	*4.1*	*3.7*	*1.7*	*0.3*	*0.2*	*0.1*	*0.1*	*	*0.1*	*0.7*	*2.0*	*14.8*

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
SOUTHWEST INDIAN OCEAN													
TROPICAL STORMS	2.0	2.2	1.7	0.6	0.2	*	*	*	*	0.3	0.3	0.8	7.4
HURRICANES	1.3	1.1	0.8	0.4	*	*	*	*	*	*	*	0.5	3.8
TROPICAL STORMS AND HURRICANES	*3.2*	*3.3*	*2.5*	*1.1*	*0.2*	*	*	*	*	*0.3*	*0.4*	*1.4*	*11.2*

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
NORTH INDIAN OCEAN													
TROPICAL STORMS	0.1	*	*	0.1	0.3	0.5	0.5	0.4	0.4	0.6	0.5	0.3	3.5
CYCLONES[1]	*	*	*	0.1	0.5	0.2	0.1	*	0.1	0.4	0.6	0.2	2.2
TROPICAL STORMS AND CYCLONES[1]	*0.1*	*	*0.1*	*0.3*	*0.7*	*0.7*	0.6	*0.4*	*0.5*	*1.0*	*1.1*	*0.5*	*5.7*

* Less than .05 [1]Winds ≥ 48 Kts.

Monthly values cannot be combined because single storms overlapping two months were counted once in each month and once in the annual.

Figure 3603b. Monthly and annual average number of storms per year for each area.

of the Philippines, and move across the Pacific toward the Philippines, Japan, and China; a few storms form in the South China Sea. The season extends from April through December. However, tropical cyclones are more common in the off-season months in this area than anywhere else. The peak of the season is July through October, when nearly 70 percent of all typhoons develop. There is a noticeable seasonal shift in storm tracks in this region. From July through September, storms move north of the Philippines and recurve, while early- and late-season typhoons move on a more westerly track through the Philippines before recurving.

North Indian Ocean—Tropical cyclones develop in the Bay of Bengal and Arabian Sea during the spring and fall. Tropical cyclones in this area form between latitudes 8°N and 15°N, except from June through September, when the little activity that does occur is confined north of about 15°N. These storms are usually short-lived and weak; however, winds of 130 knots have been encountered. They often develop as disturbances along the Intertropical Convergence Zone (ITCZ); this inhibits summertime development, since the ITCZ is usually over land during this monsoon season. However, it is sometimes displaced southward, and when this occurs, storms will form over the monsoon-flooded plains of Bengal. On the average, six cyclonic storms form each year. These include two storms that generate winds of 48 knots or greater. Another 10 tropical cyclones never develop beyond tropical depressions. The Bay of Bengal is the area of highest incidence. However, it is not unusual for a storm to move across southern India and reintensify in the Arabian Sea. This is particularly true during October, the month of highest incidence during the tropical cyclone season. It is also during this period that torrential rains from these storms, dumped over already rain-soaked areas, cause disastrous floods.

South Indian Ocean—Over the waters west of 100°E, to the east African coast, an average of 11 tropical cyclones (tropical storms and hurricanes) form each season, and about 4 reach hurricane intensity. The season is from December through March, although it is possible for a storm to form in any month. Tropical cyclones in this region usually form south of 10°S. The latitude of recurvature usually migrates from about 20°S in January to around 15°S in April. After crossing 30°S, these storms sometimes become intense extratropical lows.

Southwest Pacific and Australian Area—These tropical waters spawn an annual average of 15 tropical cyclones 4 of which reach hurricane intensity. The season extends from about December through April, although storms can form in any month. Activity is widespread in January and February, and it is in these months that tropical cyclones are most likely to affect Fiji, Samoa, and the other eastern islands. Tropical cyclones usually form in the waters from 105°E to 160°W, between 5° and 20°S. Storms affecting northern and western Australia often develop in the Timor or Arafura Sea, while those that affect the east coast form in the Coral Sea. These storms are often small, but can develop winds in excess of 130 knots. New Zealand is sometimes reached by decaying Coral Sea storms, and occasionally by an intense hurricane. In general, tropical cyclones in this region move southwestward and then recurve southeastward.

ANATOMY OF TROPICAL CYCLONES

3604. Formation

Hurricane formation was once believed to result from an intensification of convective forces which produce the towering cumulonimbus clouds of the doldrums. This view of hurricane generation held that surface heating caused warm moist air to ascend convectively to levels where condensation produced cumulonimbus clouds, which, after an inexplicable drop in atmospheric pressure, coalesced and were spun into a cyclonic motion by Coriolis force.

This hypothesis left much unexplained. Although some hurricanes develop from disturbances beginning in the doldrums, very few reach maturity in that region. Also, the high incidence of seemingly ideal convective situations does not match the low incidence of Atlantic hurricanes. Finally, the hypothesis did not explain the drop in atmospheric pressure, so essential to development of hurricane-force winds.

There is still no exact understanding of the triggering mechanism involved in hurricane generation, the balance of conditions needed to generate hurricane circulation, and the relationships between large- and small-scale atmospheric processes. But scientists today, treating the hurricane system as an atmospheric heat engine, present a more comprehensive and convincing view.

They begin with a starter mechanism in which either internal or external forces intensify the initial disturbance. The initial disturbance becomes a region into which low-level air from the surrounding area begins to flow, accelerating the convection already occurring inside the disturbance. The vertical circulation becomes increasingly well organized as water vapor in the ascending moist layer is condensed (releasing large amounts of heat energy to drive the wind system), and as the system is swept into a counterclockwise cyclonic spiral. But this incipient hurricane would soon fill up because of inflow at lower levels, unless the chimney in which converging air surges upward is provided the exhaust mechanism of high-altitude winds.

These high-altitude winds pump ascending air out of

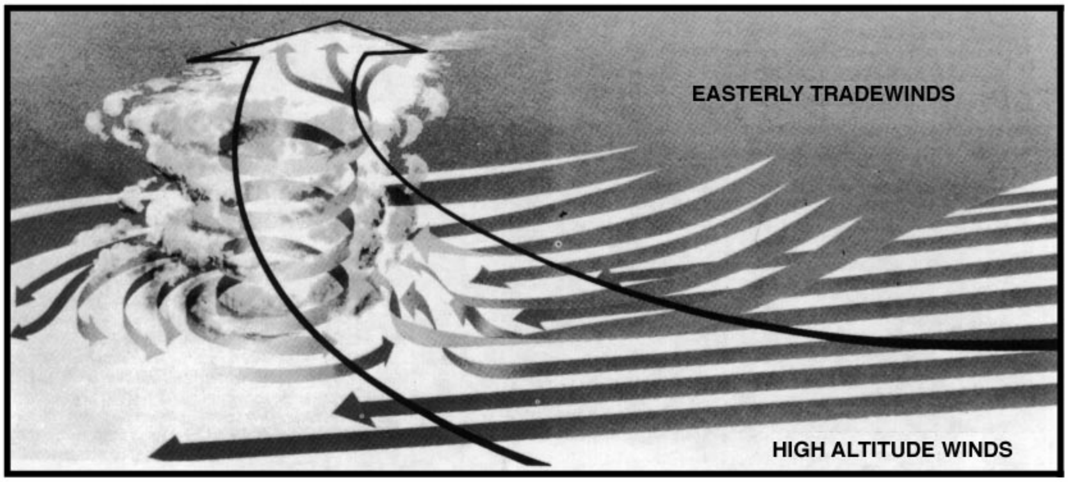


Figure 3604. Pumping action of high-altitude winds.

the cyclonic system, into a high-altitude anticyclone, which transports the air well away from the disturbance, before sinking occurs. Thus, a large scale vertical circulation is set up, in which low-level air is spiraled up the cyclonic twisting of the disturbance, and, after a trajectory over the sea, returned to lower altitudes some distance from the storm. This pumping action-and the heat released by the ascending air may account for the sudden drop of atmospheric pressure at the surface, which produces the steep pressure gradient along which winds reach hurricane proportions.

It is believed that the interaction of low-level and high-altitude wind systems determines the intensity the hurricane will attain. If less air is pumped out than converges at low levels, the system will fill and die out. If more is pumped out than flows in, the circulation will be sustained and will intensify.

Scientists have found that any process which increases the rate of low-level inflow is favorable for hurricane development, provided the inflowing air carries sufficient heat and moisture to fuel the hurricane's power system. It has also been shown that air above the developing disturbance, at altitudes between 20,000 and 40,000 feet, increases 1° to 3° in temperature about 24 hours before the disturbance develops into a hurricane. But it is not known whether low-level inflow and high-level warming cause hurricanes. They could very well be measurable symptoms of another effect which actually triggers the storm's increase to hurricane intensity.

The view of hurricanes as atmospheric engines is necessarily a general one. The exact role of each contributor is not completely understood. The engine seems to be both inefficient and unreliable; a myriad of delicate conditions must be satisfied for the atmosphere to produce a hurricane. Their relative infrequency indicates that many potential hurricanes dissipate before developing into storms.

3605. Portrait Of A Hurricane

In the early life of the hurricane, the spiral covers an area averaging 100 miles in diameter with winds of 64 knots and greater, and spreads gale-force winds over a 400-mile diameter. The cyclonic spiral is marked by heavy cloud bands from which torrential rains fall, separated by areas of light rain or no rain at all. These spiral bands ascend in decks of cumulus and cumulonimbus clouds to the convective limit of cloud formation, where condensing water vapor is swept off as ice-crystal wisps of cirrus clouds. Thunderstorm electrical activity is observed in these bands, both as lightning and as tiny electrostatic discharges.

In the lower few thousand feet, air flows in through the cyclone, and is drawn upward through ascending columns of air near the center. The size and intensity decrease with altitude, the cyclonic circulation being gradually replaced above 40,000 feet by an anticyclonic circulation centered hundreds of miles away, which is the exhaust system of the hurricane heat engine.

At lower levels, where the hurricane is more intense, winds on the rim of the storm follow a wide pattern, like the slower currents around the edge of a whirlpool; and, like those currents, these winds accelerate as they approach the center of the vortex. The outer band has light winds at the rim of the storm, perhaps no more than 25 knots; within 30 miles of the center, winds may have velocities exceeding 130 knots. The inner band is the region of maximum wind velocity, where the storm's worst winds are felt, and where ascending air is chimneyed upward, releasing heat to drive the storm. In most hurricanes, these winds reach 85 knots, and more than 170 knots in severe storms.

In the hurricane, winds flow toward the low pressure in the warm, comparatively calm core. There, converging air is whirled upward by convection, the mechanical thrusting of other converging air, and the pumping action of high-altitude circulations. This spiral is marked by the thick cloud walls curling inward toward the storm center, releasing heavy precipitation and enormous quantities of heat energy. At the center, surrounded by a band in which this strong vertical circulation is greatest, is the **eye** of the hurricane.

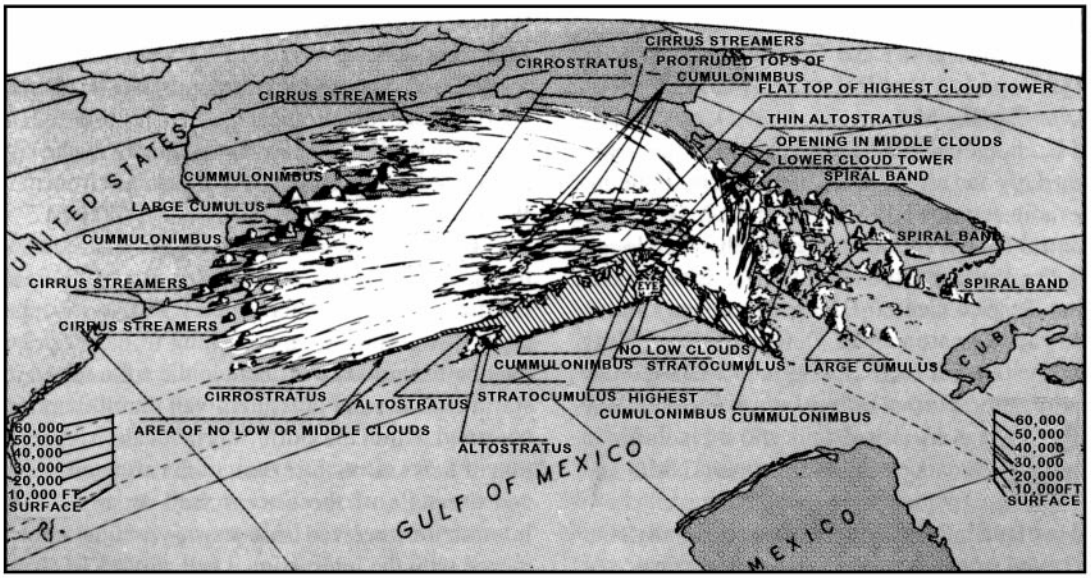


Figure 3605. Cutaway view of a hurricane greatly exaggerated in vertical dimension. Actual hurricanes are less than 50,000 feet high and may have a diameter of several hundred miles.

On the average, eye diameter is about 14 miles, although diameters of 25 miles are not unusual. From the heated tower of maximum winds and cumulonimbus clouds, winds diminish rapidly to something less than 15 miles per hour in the eye; at the opposite wall, winds increase again, but come from the opposite direction because of the cyclonic circulation of the storm. This sudden transformation of storm into comparative calm, and from calm into violence from another quarter is spectacular. The eye's abrupt existence in the midst of opaque rain squalls and hurricane winds, the intermittent bursts of blue sky and sunlight through light clouds in the core of the cyclone, and the galleried walls of cumulus and cumulonimbus clouds are unforgettable.

Every hurricane is individual, and the more or less orderly circulation described here omits the extreme variability and instability within the storm system. Pressure and temperature gradients fluctuate wildly across the storm as the hurricane maintains its erratic life. If it is an August storm, its average life expectancy is 12 days; if a July or November storm, it lives an average of 8 days.

3606. Life Of A Tropical Cyclone

Reports from ships in the vicinity of an **easterly wave** (a westward-moving trough of low pressure embedded in deep easterlies) may indicate that the atmospheric pressure in the region has fallen more than 5 millibars in the past 24 hours. This is cause for alarm, because in the Tropics pressure varies little; the normal diurnal pressure change is only about 3 millibars. Satellite pictures may indicate thickening middle and high clouds. Squalls are reported ahead of the easterly wave, and wind reports indicate a cyclonic circulation is forming. The former easterly wave, now classified a tropical disturbance, is moving westward at 10 knots under the canopy of a large high-pressure system aloft. Sea surface temperatures in the vicinity are in the 28°-30°C range.

Within 48 hours winds increase to 25 knots near the center of definite circulation, and central pressure has dropped below 1000 millibars. The disturbance is now classified as a tropical depression. Soon the circulation extends out to 100 miles and upward to 20,000 feet. Winds near the center increase to gale force, central pressure falls below 990 millibars, and towering cumulonimbus clouds shield a developing eye; a tropical storm has developed.

Satellite photographs now reveal a tightly organized tropical cyclone, and reconnaissance reports indicate maximum winds of 80 knots around a central pressure of 980 millibars; a hurricane has developed. A ship to the right (left in the Southern Hemisphere) of the hurricane's center (looking toward the direction of storm movement) reports 30-foot seas. The hurricane is rapidly maturing as it continues westward.

A few days later the hurricane reaches its peak. The satellite photographs show a textbook picture, as 120-knot winds roar around a 940-millibar pressure center; hurricane-force winds extend 50 miles in all directions, and seas are reported up to 40 feet. There is no further deepening now, but the hurricane begins to expand. In 2 days, gales extend out to 200 miles, and hurricane winds out to 75 miles. Then the hurricane slows and begins to recurve; this turning marks the beginning of its final phase.

The hurricane accelerates, and, upon reaching temper-

ate latitudes, it begins to lose its tropical characteristics. The circulation continues to expand, but now cold air is intruding (cold air, cold water, dry air aloft, and land, aid in the decay of a tropical cyclone). The winds gradually abate as the concentrated storm disintegrates. The warm core survives for a few more days before the transformation to a large extratropical low-pressure system is complete.

Not all tropical cyclones follow this average pattern. Most falter in the early stages, some dissipate over land, and others remain potent for several weeks.

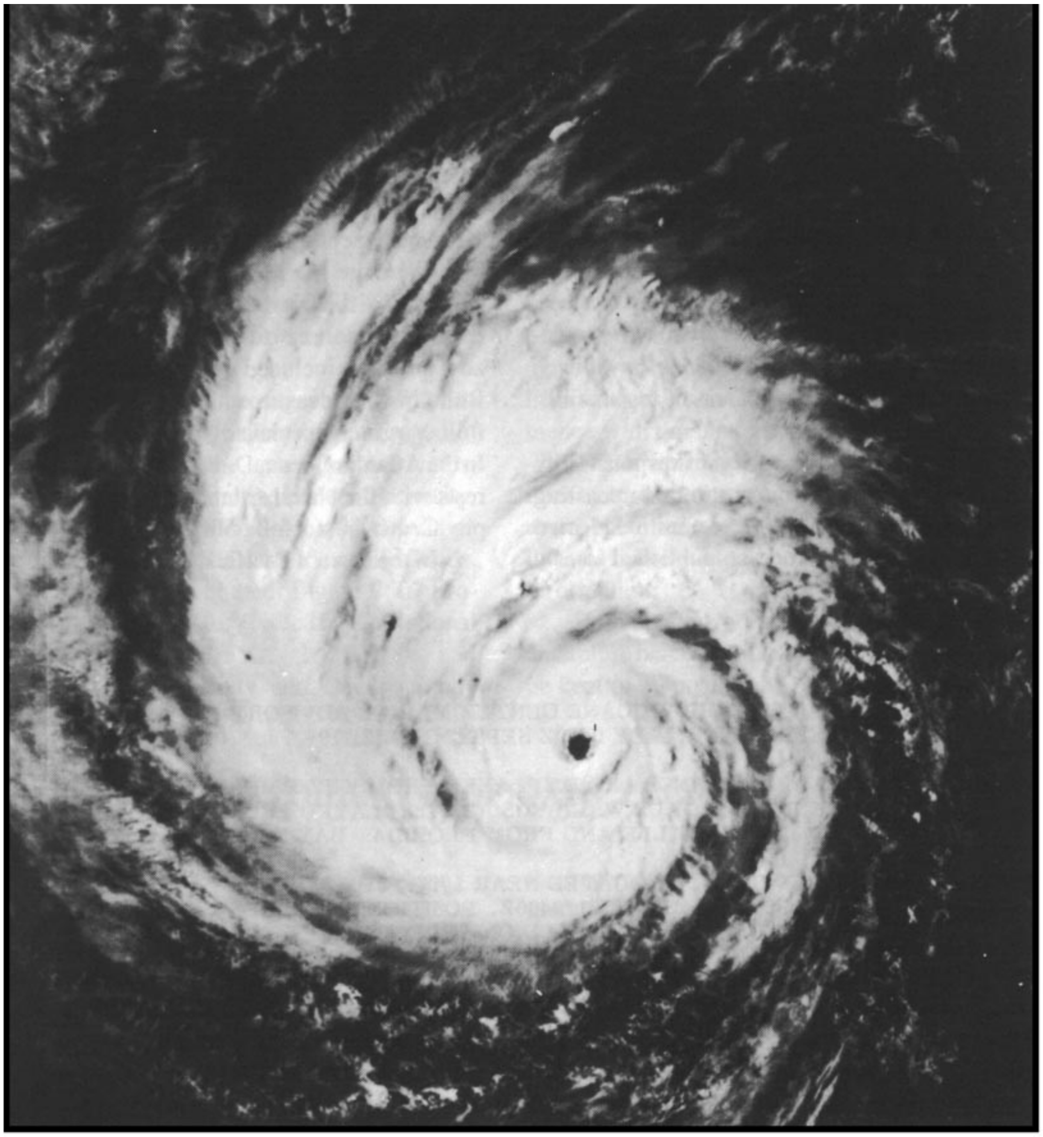


Figure 3606. Satellite photograph of a hurricane.

FORECASTING AND PREDICTING TROPICAL CYCLONES

3607. Weather Broadcasts And Radiofacsimile

The marine weather broadcast and radiofacsimile weather maps are the most important tools for avoiding tropical cyclones. These broadcasts, covering all tropical areas, provide information about the tropical cyclone's location, maximum winds and seas, and future conditions expected.

The U S. Navy, the National Oceanic and Atmospheric Administration, and the U.S. Air Force have developed a highly effective surveillance system for the tropical cy-

clone-prone areas of the world. Routine and special weather reports (from land stations, ships at sea, aircraft; weather satellite imagery; radar reports from land stations; special reports from ships at sea; and the specially instrumented weather reconnaissance aircraft of National Oceanic and Atmospheric Administration and the U.S. Air Force) enable accurate detection, location, and tracking of tropical cyclones. International cooperation is effective. Data buoys, both moored and drifting, provide another source of information.

The tropical warning services have three principal functions:

1. The collection and analysis of the necessary observational data.
2. The preparation of timely and accurate forecasts and warnings.
3. The rapid and efficient distribution of advisories, warnings, and all other pertinent information.

To provide timely and accurate information and warnings regarding tropical cyclones, the oceans have been divided into overlapping geographical areas of responsibility.

For detailed information on the areas of responsibility of the countries participating in the international forecasting and warning program, and radio aids, refer to Selected Worldwide Marine Weather Broadcasts, published jointly by the Naval Meteorology and Oceanography Command and the National Weather Service.

Although the areas of forecasting responsibility are fairly well defined for the Department of Defense, the international and domestic civilian system provides many overlaps and is dependent upon qualitative factors. For example, when a tropical storm or hurricane is traveling westward and crosses 35°W longitude, the continued issuance of forecasts and warnings to the general public, shipping interests, etc., becomes the responsibility of the National Hurricane Center of the National Weather Service at Miami, Florida. When a tropical storm or hurricane crosses 35°W longitude traveling from west to east, the National Hurricane Center ceases to issue formal public advisories, but will issue marine bulletins on any dangerous tropical cyclone in the North Atlantic, if it is of importance or constitutes a threat to shipping and other interests. These advisories are included in National Weather Service Marine Bulletins broadcast to ships over radio station NAM Norfolk, Virginia. Special advisories may be issued at any time. In the Atlantic Ocean, Department of Defense responsibility rests with the Naval Atlantic Meteorology and Oceanography Center in Norfolk, Virginia.

In the eastern Pacific east of longitude 140°W, respon-

NOAA/NATIONAL HURRICANE CENTER MARINE ADVISORY NUMBER 13 HURRICANE LADY 0400Z SEPTEMBER 21 19--.

HURRICANE WARNINGS ARE DISPLAYED FROM KEY LARGO TO CAPE KENNEDY. GALE WARNINGS ARE DISPLAYED FROM KEY WEST TO JACKSONVILLE AND FROM FLORIDA BAY TO CEDAR KEY.

HURRICANE CENTER LOCATED NEAR LATITUDE 25.5 NORTH LONGITUDE 78.5 WEST AT 21/0400Z. POSITION EXCELLENT ACCURATE WITHIN 10 MILES BASED ON AIR FORCE RECONNAISSANCE AND SYNOPTIC REPORTS.

PRESENT MOVEMENT TOWARD THE WEST NORTHWEST OR 285 DEGREES AT 10 KT. MAX SUSTAINED WINDS OF 100 KT NEAR CENTER WITH GUSTS TO 160 KT.
MAX WINDS OVER INLAND AREAS 35 KT.
RAD OF 65 KT WINDS 90 NE 60 SE 80 SW 90 NW QUAD.
RAD OF 50 KT WINDS 120 NE 70 SE 90 SW 120 NW QUAD.
RAD OF 30 KT WINDS 210 NE 210 SE 210 SW 210 NW QUAD.
REPEAT CENTER LOCATED 25.5N 78.3W AT 21/0400Z.

12 HOUR FORECAST VALID 21/1600Z LATITUDE 26.0N LONGITUDE 80.5W.
MAX WINDS OF 100 KT NEAR CENTER WITH GUSTS TO 160 KT.
MAX WINDS OVER INLAND AREAS 65 KT.
RADIUS OF 50 KT WINDS 120 NE 70 SE 90 SW 120 NW QUAD.
24 HOUR FORECAST VALID 22/0400Z LATITUDE 26.0N LONGITUDE 83.0W.
MAX WINDS OF 75 KT NEAR CENTER WITH GUSTS TO 120 KT.
MAX WINDS OVER INLAND AREAS 45 KT.
RADIUS OF 50 KT WINDS 120 NE 120 SE 120 SW 120 NW QUAD.

STORM TIDE OF 9 TO 12 FT SOUTHEAST FLA COAST GREATER MIAMI AREA TO THE PALM BEACHES.

NEXT ADVISORY AT 21/1000Z.

Figure 3607. Example of marine advisory issued by National Hurricane Center.

sibility for the issuance of tropical storm and hurricane advisories and warnings for the general public, merchant shipping, and other interests rests with the National Weather Service Eastern Pacific Hurricane Center, San Francisco, California. The Department of Defense responsibility rests with the Naval Pacific Meteorology and Oceanography Center, Pearl Harbor, Hawaii. Formal advisories and warnings are issued daily and are included in the marine bulletins broadcast by radio stations KFS, NMC, and NMQ.

In the central Pacific (between the meridian and longitude 140°W), the civilian responsibility rests with the National Weather Service Central Pacific Hurricane Center, Honolulu, Hawaii. Department of Defense responsibility rests with the Naval Pacific Meteorology and Oceanography Center in Pearl Harbor. Formal tropical storm and hurricane advisories and warnings are issued daily and are included in the marine bulletins broadcast by radio station NMO and NRV.

Tropical cyclone information messages generally contain position of the storm, intensity, direction and speed of movement, and a description of the area of strong winds. Also included is a forecast of future movement and intensity. When the storm is likely to affect any land area, details on when and where it will be felt, and data on tides, rain, floods, and maximum winds are also included. Figure 3607 provides an example of a marine advisory issued by the National Hurricane Center.

The Naval Pacific Meteorology and Oceanography Center Center-West/Joint Typhoon Warning Center (NPMOC-W/JTWC) in Guam is responsible for all U.S. tropical storm and typhoon advisories and warnings from the 180th meridian westward to the mainland of Asia. A secondary area of responsibility extends westward to longitude 90°E. Whenever a tropical cyclone is observed in the western North Pacific area, serially numbered warnings, bearing an “immediate” precedence are broadcast from the NPMOC-W/JTWC at 0000, 0600, 1200, and 1800 GMT.

The responsibility for issuing gale and storm warnings for the Indian Ocean, Arabian Sea, Bay of Bengal, Western Pacific, and South Pacific rests with many countries. In general, warnings of approaching tropical cyclones which may be hazardous will include the following information: storm type, central pressure given in millibars, wind speed observed within the storm, storm location, speed and direction of movement, the extent of the affected area, visibility, and the state of the sea, as well as any other pertinent information received. All storm warning messages commence with the international call sign “TTT.”

These warnings are broadcast on specified radio frequency bands immediately upon receipt of the information and at specific intervals thereafter. Generally, the broadcast interval is every 6 to 8 hours, depending upon receipt of new information.

Bulletins and forecasts are excellent guides to the present and future behavior of the tropical cyclone, and a plot should be kept of all positions.

AVOIDING TROPICAL CYCLONES

3608. Approach And Passage Of A Tropical Cyclone

An early indication of the approach of a tropical cyclone is the presence of a long swell. In the absence of a tropical cyclone, the crests of swell in the deep waters of the Atlantic pass at the rate of perhaps eight per minute. Swell generated by a hurricane is about twice as long, the crests passing at the rate of perhaps four per minute. Swell may be observed several days before arrival of the storm.

When the storm center is 500 to 1,000 miles away, the barometer usually rises a little, and the skies are relatively clear. Cumulus clouds, if present at all, are few in number and their vertical development appears suppressed. The barometer usually appears restless, pumping up and down a few hundredths of an inch.

As the tropical cyclone comes nearer, a cloud sequence begins which resembles that associated with the approach of a warm front in middle latitudes. Snow-white, fibrous “mare’s tails” (cirrus) appear when the storm is about 300 to 600 miles away. Usually these seem to converge, more or less, in the direction from which the storm is approaching. This convergence is particularly apparent at about the time of sunrise and sunset.

Shortly after the cirrus appears, but sometimes before, the barometer starts a long, slow fall. At first the fall is so gradual that it only appears to alter somewhat the normal daily cycle (two maxima and two minima in the Tropics). As the rate of fall increases, the daily pattern is completely lost in the more or less steady fall.

The cirrus becomes more confused and tangled, and then gradually gives way to a continuous veil of cirrostratus. Below this veil, altostratus forms, and then stratocumulus. These clouds gradually become more dense, and as they do so, the weather becomes unsettled. A fine, mist-like rain begins to fall, interrupted from time to time by rain showers. The barometer has fallen perhaps a tenth of an inch.

As the fall becomes more rapid, the wind increases in gustiness, and its speed becomes greater, reaching perhaps 22 to 40 knots (Beaufort 6-8). On the horizon appears a dark wall of heavy cumulonimbus, called the **bar** of the storm. This is the heavy bank of clouds comprising the main mass of the cyclone. Portions of this heavy cloud become detached from time to time, and drift across the sky, accompanied by rain squalls and wind of increasing speed. Between squalls, the cirrostratus can be seen through breaks in the stratocumulus.

As the bar approaches, the barometer falls more rapidly and wind speed increases. The seas, which have been gradu-

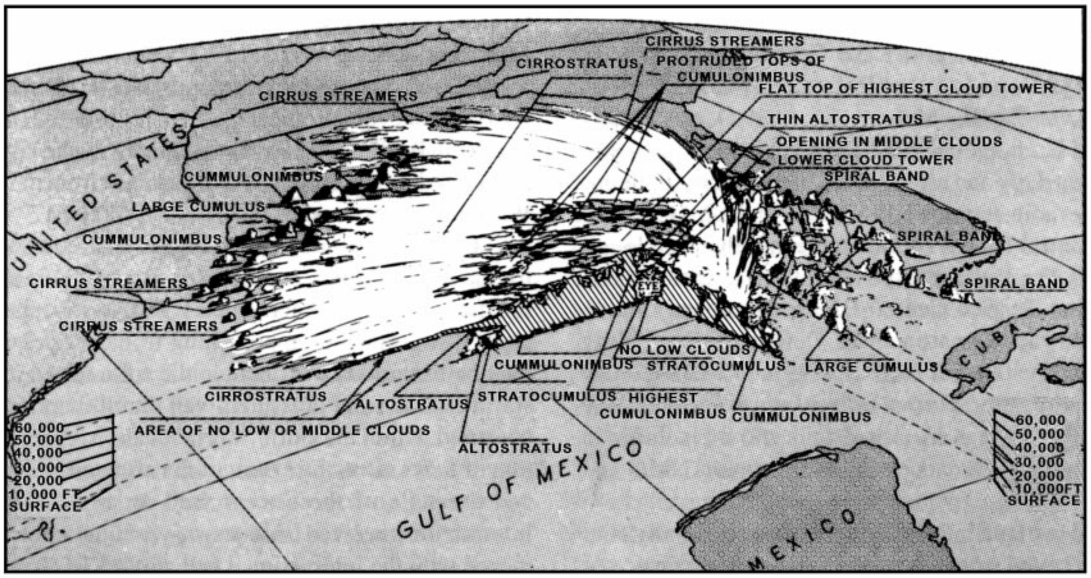


Figure 3608. Typical hurricane cloud formations.

ally mounting, become tempestuous. Squall lines, one after the other, sweep past in ever increasing number and intensity.

With the arrival of the bar, the day becomes very dark, squalls become virtually continuous, and the barometer falls precipitously, with a rapid increase in wind speed. The center may still be 100 to 200 miles away in a fully developed tropical cyclone. As the center of the storm comes closer, the ever-stronger wind shrieks through the rigging, and about the superstructure of the vessel. As the center approaches, rain falls in torrents. The wind fury increases. The seas become mountainous. The tops of huge waves are blown off to mingle with the rain and fill the air with water. Visibility is virtually zero in blinding rain and spray. Even the largest and most seaworthy vessels become virtually unmanageable, and may sustain heavy damage. Less sturdy vessels may not survive. Navigation virtually stops as safety of the vessel becomes the only consideration. The awesome fury of this condition can only be experienced. Words are inadequate to describe it.

If the eye of the storm passes over the vessel, the winds suddenly drop to a breeze as the wall of the eye passes. The rain stops, and the skies clear sufficiently to permit the sun or stars to shine through holes in the comparatively thin cloud cover. Visibility improves. Mountainous seas approach from all sides in complete confusion. The barometer reaches its lowest point, which may be 1 $^{1}/_{2}$ or 2 inches below normal in fully developed tropical cyclones. As the wall on the opposite side of the eye arrives, the full fury of the wind strikes as suddenly as it ceased, but from the opposite direction. The sequence of conditions that occurred during approach of the storm is reversed, and passes more quickly, as the various parts of the storm are not as wide in the rear of a storm as on its forward side.

Typical cloud formations associated with a hurricane are shown in Figure 3608.

3609. Locating The Center Of A Tropical Cyclone

If intelligent action is to be taken to avoid the full fury of a tropical cyclone, early determination of its location and direction of travel relative to the vessel is essential. The bulletins and forecasts are an excellent general guide, but they are not infallible, and may be sufficiently in error to induce a mariner in a critical position to alter course so as to unwittingly increase the danger to his vessel. Often it is possible, using only those observations made aboard ship, to obtain a sufficiently close approximation to enable the vessel to maneuver to the best advantage.

The presence of an exceptionally long swell is usually the first visible indication of the existence of a tropical cyclone. In deep water it approaches from the general direction of origin (the position of the storm center when the swell was generated). However, in shoaling water this is a less reliable indication because the direction is changed by refraction, the crests being more nearly parallel to the bottom contours.

When the cirrus clouds appear, their point of convergence provides an indication of the direction of the storm center. If the storm is to pass well to one side of the observer, the point of convergence shifts slowly in the direction of storm movement. If the storm center will pass near the observer, this point remains steady. When the bar becomes visible, it appears to rest upon the horizon for several hours. The darkest part of this cloud is in the direction of the storm center. If the storm is to pass to one side, the bar appears to drift slowly along the horizon. If the storm is heading di-

rectly toward the observer, the position of the bar remains fixed. Once within the area of the dense, low clouds, one should observe their direction of movement, which is almost exactly along the isobars, with the center of the storm being 90° from the direction of cloud movement (left of direction of movement in the Northern Hemisphere, and right in the Southern Hemisphere).

The winds are probably the best guide to the direction of the center of a tropical cyclone. The circulation is cyclonic, but because of the steep pressure gradient near the center, the winds there blow with greater violence and are more nearly circular than in extratropical cyclones.

According to **Buys Ballot's law**, an observer whose back is to the wind has the the low pressure on his left in the Northern Hemisphere, and on his right in the Southern Hemisphere. If the wind followed circular isobars exactly, the center would be exactly 90° from behind when facing away from the wind. However, the track of the wind is usually inclined somewhat toward the center, so that the angle from dead astern varies between perhaps 90° to 135°. The inclination varies in different parts of the same storm. It is least in front of the storm, and greatest in the rear, since the actual wind is the vector sum of the pressure gradient and the motion of the storm along the track. A good average is perhaps 110° in front, and 120-135° in the rear. These values apply when the storm center is still several hundred miles away. Closer to the center, the wind blows more nearly along the isobars, the inclination being reduced by one or two points at the wall of the eye. Since wind direction usually shifts temporarily during a squall, its direction at this time should not be used for determining the position of the center. The approximate relationship of wind to isobars and storm center in the Northern Hemisphere is shown in Figure 3609a.

When the center is within radar range, it will probably be visible on the scope. However, since the radar return is predominantly from the rain, results can be deceptive, and other indications should not be neglected. Figure 3609b shows a radar PPI presentation of a tropical cyclone. If the eye is out of range, the spiral bands (Figure 3609b) may indicate its direction from the vessel. Tracking the eye or upwind portion of the spiral bands enables determining the direction and speed of movement; this should be done for at

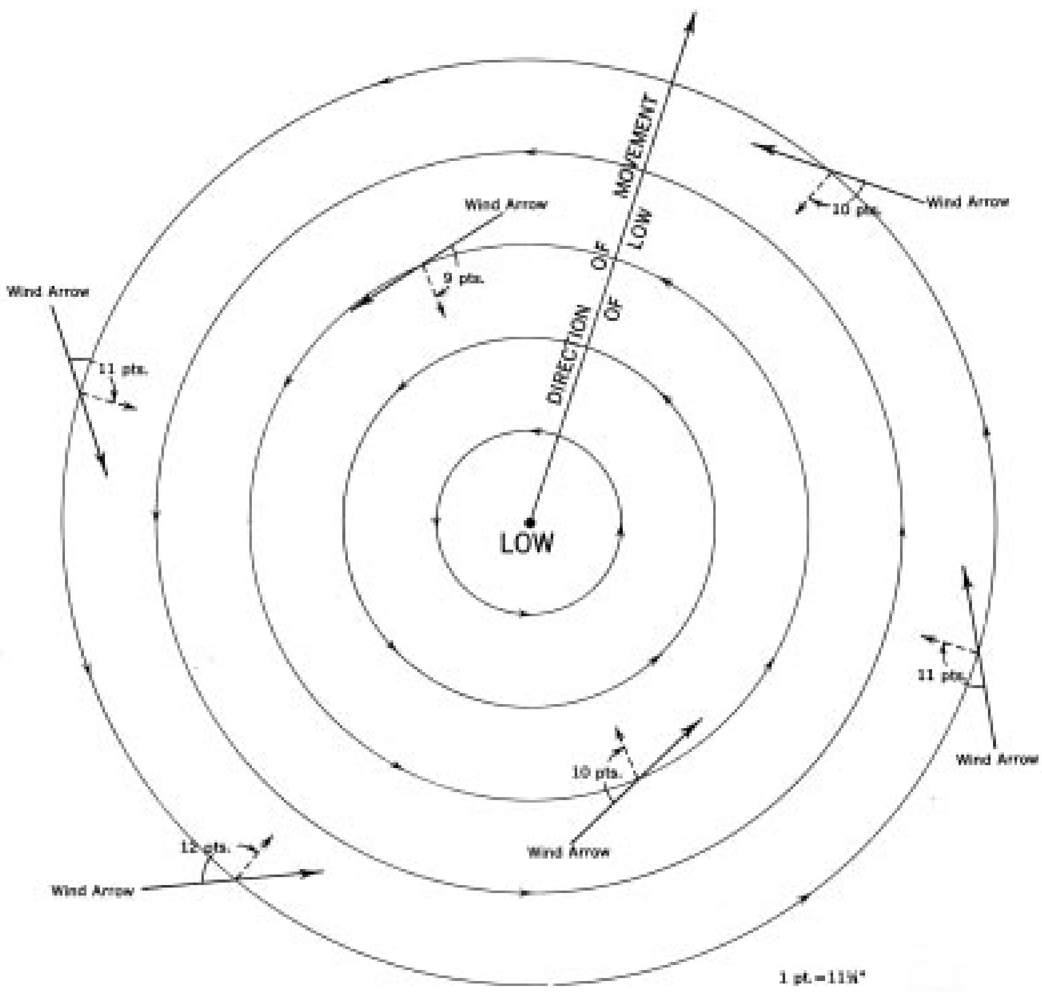


Figure 3609a. Approximate relationship of wind to isobars and storm center in the Northern Hemisphere.

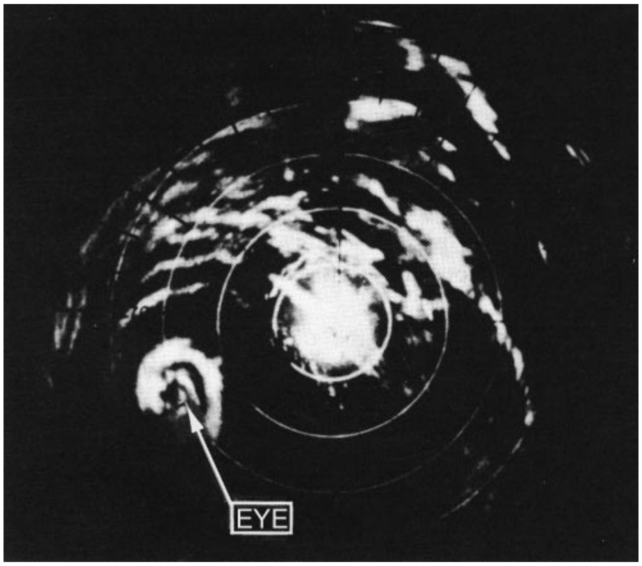


Figure 3609b. Radar PPI presentation of a tropical cyclone.

least 1 hour because the eye tends to oscillate. The tracking of individual cells, which tend to move tangentially around the eye, for 15 minutes or more, either at the end of the band or between bands, will provide an indication of the wind speed in that area of the storm.

Distance from the storm center is more difficult to determine than direction. Radar is perhaps the best guide. However, the rate of fall of the barometer is some indication.

3610. Statistical Analysis Of Barometric Pressure

The lowest-sea-level pressure ever recorded was 877 millibars in typhoon Ida, on September 24, 1958. The observation was taken by a reconnaissance aircraft dropsonde, some 750 miles east of Luzon, Philippines. This observation was obtained again in typhoon Nora on October 6, 1973. The lowest barometric reading of record for the United States is 892.3 millibars, obtained during a hurricane at Lower Matecumbe Key, Florida, in September 1935. In hurricane Camille in 1969, a 905 millibar pressure was measured by reconnaissance aircraft. During a 1927 typhoon, the S.S. Sapoeroea recorded a pressure of 886.6 millibars, the lowest sea-level pressure reported from a ship. Pressure has been observed to drop more than 33 millibars per hour, with a pressure gradient amounting to a change of 3.7 millibars per mile.

A method for alerting the mariner to possible tropical cyclone formation involves a statistical comparison of observed weather parameters with the climatology (30 year averaged conditions) for those parameters. Significant fluctuations away from these average conditions could mean the onset of severe weather. One such statistical method involves a comparison of mean surface pressure in the tropics with the standard deviation (s.d.) of surface pressure. Any significant deviation from the norm could indicate proximity to a tropical cyclone. Analysis shows that surface pressure can be expected to be lower than the mean minus 1 s.d. less than 16% of the time, lower than the mean minus 1.5 s.d. less than 7% of the time, and lower than the mean minus 2 s.d. less than 3% of the time. Comparison of the observed pressure with the mean will indicate how “unusual” the present conditions are.

As an example, assume the mean surface pressure in the South China Sea to be about 1005 mb during August with a s.d. of about 2 mb. Therefore, surface pressure can be expected to fall below 1003 mb about 16% of the time and below 1000 mb about 7% of the time. Ambient pressure any lower than that would alert the mariner to the possible onset of heavy weather. Charts showing the mean surface pressure and the s.d. of surface pressure for various global regions can be found in the U.S. Navy Marine Climatic Atlas of the World.

3611. Maneuvering To Avoid The Storm Center

The safest procedure with respect to tropical cyclones is to avoid them. If action is taken sufficiently early, this is simply a matter of setting a course that will take the vessel well to one side of the probable track of the storm, and then continuing to plot the positions of the storm center as given in the weather bulletins, revising the course as needed.

However, this is not always possible. If the ship is found to be within the storm area, the proper action to take depends in part upon its position relative to the storm center and its direction of travel. It is customary to divide the circular area of the storm into two parts.

In the Northern Hemisphere, that part to the right of the storm track (facing in the direction toward which the storm is moving) is called the **dangerous semicircle**. It is considered dangerous because (1) the actual wind speed is greater than that due to the pressure gradient alone, since it is augmented by the forward motion of the storm, and (2) the direction of the wind and sea is such as to carry a vessel into the path of the storm (in the forward part of the semicircle).

The part to the left of the storm track is called the **less dangerous semicircle**, or **navigable semicircle**. In this part, the wind is decreased by the forward motion of the storm, and the wind blows vessels away from the storm track (in the forward part). Because of the greater wind speed in the dangerous semicircle, the seas are higher than in the less dangerous semicircle. In the Southern Hemisphere, the dangerous semicircle is to the left of the storm track, and the less dangerous semicircle is to the right of the storm track.

A plot of successive positions of the storm center should indicate the semicircle in which a vessel is located. However, if this is based upon weather bulletins, it may not be a reliable guide because of the lag between the observations upon which the bulletin is based and the time of reception of the bulletin, with the ever-present possibility of a change in the direction of the storm. The use of radar eliminates this lag at short range, but the return may not be a true indication of the center. Perhaps the most reliable guide is the wind. Within

the cyclonic circulation, a wind shifting to the right in the northern hemisphere and to the left in the southern hemisphere indicates the vessel is probably in the dangerous semicircle. A steady wind shift opposite to this indicates the vessel is probably in the less dangerous semicircle.

However, if a vessel is underway, its own motion should be considered. If it is outrunning the storm or pulling rapidly toward one side (which is not difficult during the early stages of a storm, when its speed is low), the opposite effect occurs. This should usually be accompanied by a rise in atmospheric pressure, but if motion of the vessel is nearly along an isobar, this may not be a reliable indication. If in doubt, the safest action is usually to stop long enough to define the proper semicircle. The loss in time may be more than offset by the minimizing of the possibility of taking the wrong action, increasing the danger to the vessel. If the wind direction remains steady (for a vessel which is stopped), with increasing speed and falling barometer, the vessel is in or near the path of the storm. If it remains steady with decreasing speed and rising barometer, the vessel is near the storm track, behind the center.

The first action to take if the ship is within the cyclonic circulation is to determine the position of his vessel with respect to the storm center. While the vessel can still make considerable way through the water, a course should be selected to take it as far as possible from the center. If the vessel can move faster than the storm, it is a relatively simple matter to outrun the storm if sea room permits. But when the storm is faster, the solution is not as simple. In this case, the vessel, if ahead of the storm, will approach nearer to the center. The problem is to select a course that will produce the greatest possible minimum distance. This is best determined by means of a relative movement plot, as shown in the following example solved on a maneuvering board.

Example: *A tropical cyclone is estimated to be moving in direction 320° at 19 knots. Its center bears 170°, at an estimated distance of 200 miles from a vessel which has a maximum speed of 12 knots.*

Required:

(1) *The course to steer at 12 knots to produce the greatest possible minimum distance between the vessel and the storm center.*
(2) *The distance to the center at nearest approach.*
(3) *Elapsed time until nearest approach.*

Solution: *(Figure 3611) Consider the vessel remaining at the center of the plot throughout the solution, as on a radar PPI.*

(1) To locate the position of the storm center relative to the vessel, plot point C at a distance of 200 miles (scale 20:1) in direction 170° from the center of the diagram. From the center of the diagram, draw RA, the speed vector of the storm center, in direction 320°, speed 19 knots (scale 2:1). From A draw a line tangent to the 12-knot speed circle (labeled 6 at scale 2:1) on the side opposite the storm center. From the center of the diagram, draw a perpendicular to this tangent line, locating point B. The line RB is the required speed vector for the vessel. Its direction, 011°, is the required course.

(2) The path of the storm center relative to the vessel will be along a line from C in the direction BA, if both storm and vessel maintain course and speed. The point of nearest approach will be at D, the foot of a perpendicular from the center of the diagram. This distance, at scale 20:1, is 187 miles.

(3) The length of the vector BA (14.8 knots) is the speed of the storm with respect to the vessel. Mark this on the lowest scale of the nomogram at the bottom of the diagram. The relative distance CD is 72 miles, by measurement. Mark this (scale 10:1) on the middle scale at the bottom of the diagram. Draw a line between the two points and extend it to intersect the top scale at 29.2 (292 at 10:1 scale). The elapsed time is therefore 292 minutes, or 4 hours 52 minutes.

Answers: *(1) C 011°, (2) D 187 mi., (3) $4^h\ 52^m$.*
The storm center will be dead astern at its nearest approach.

As a general rule, for a vessel in the Northern Hemisphere, safety lies in placing the wind on the starboard bow in the dangerous semicircle and on the starboard quarter in the less dangerous semicircle. If on the storm track ahead of the storm, the wind should be put about 160° on the starboard quarter until the vessel is well within the less dangerous semicircle, and the rule for that semicircle then followed. In the Southern Hemisphere the same rules hold, but with respect to the port side. With a faster than average vessel, the wind can be brought a little farther aft in each case. However, as the speed of the storm increases along its track, the wind should be brought farther forward. If land interferes with what would otherwise be the best maneuver, the solution should be altered to fit the circumstances.

If the vessel is faster than the storm, it is possible to overtake it. In this case, the only action usually needed is to slow enough to let the storm pull ahead.

In all cases, one should be alert to changes in the direction of movement of the storm center, particularly in the area where the track normally curves toward the pole. If the storm maintains its direction and speed, the ship's course should be maintained as the wind shifts.

If it becomes necessary for a vessel to heave to, the characteristics of the vessel should be considered. A power vessel is concerned primarily with damage by direct action of the sea. A good general rule is to heave to with head to the sea in the dangerous semicircle, or stern to the sea in the less dangerous semicircle. This will result in greatest amount of headway away from the storm center, and least amount of leeway toward it. If a vessel handles better with the sea astern or on the quarter, it may be placed in this position in the less dangerous semicircle or in the rear half of the dangerous semicircle, but never in the forward half of the dangerous semicircle. It has been reported that when the

wind reaches hurricane speed and the seas become confused, some ships ride out the storm best if the engines are stopped, and the vessel is left to seek its own position, or lie ahull. In this way, it is said, the ship rides with the storm instead of fighting against it.

In a sailing vessel attempting to avoid a storm center, one should steer courses as near as possible to those prescribed above for power vessels. However, if it becomes necessary for such a vessel to heave to, the wind is of greater concern than the sea. A good general rule always is to heave to on whichever tack permits the shifting wind to draw aft. In the Northern Hemisphere, this is the starboard tack in the dangerous semicircle, and the port tack in the less dangerous semicircle. In the Southern Hemisphere these are reversed.

While each storm requires its own analysis, and frequent or continual resurvey of the situation, the general rules for a steamer may be summarized as follows:

Northern Hemisphere

Right or dangerous semicircle: Bring the wind on the starboard bow (045˚ relative), hold course and make as much way as possible. If necessary, heave to with head to the sea.

Left or less dangerous semicircle: Bring the wind on the starboard quarter (135° relative), hold course and make as much way as possible. If necessary, heave to with stern to the sea.

On storm track, ahead of center: Bring the wind 2 points on the starboard quarter (about 160° relative), hold course and make as much way as possible. When well within the less dangerous semicircle, maneuver as indicated above.

On storm track, behind center: Avoid the center by the best practicable course, keeping in mind the tendency of tropical cyclones to curve northward and eastward.

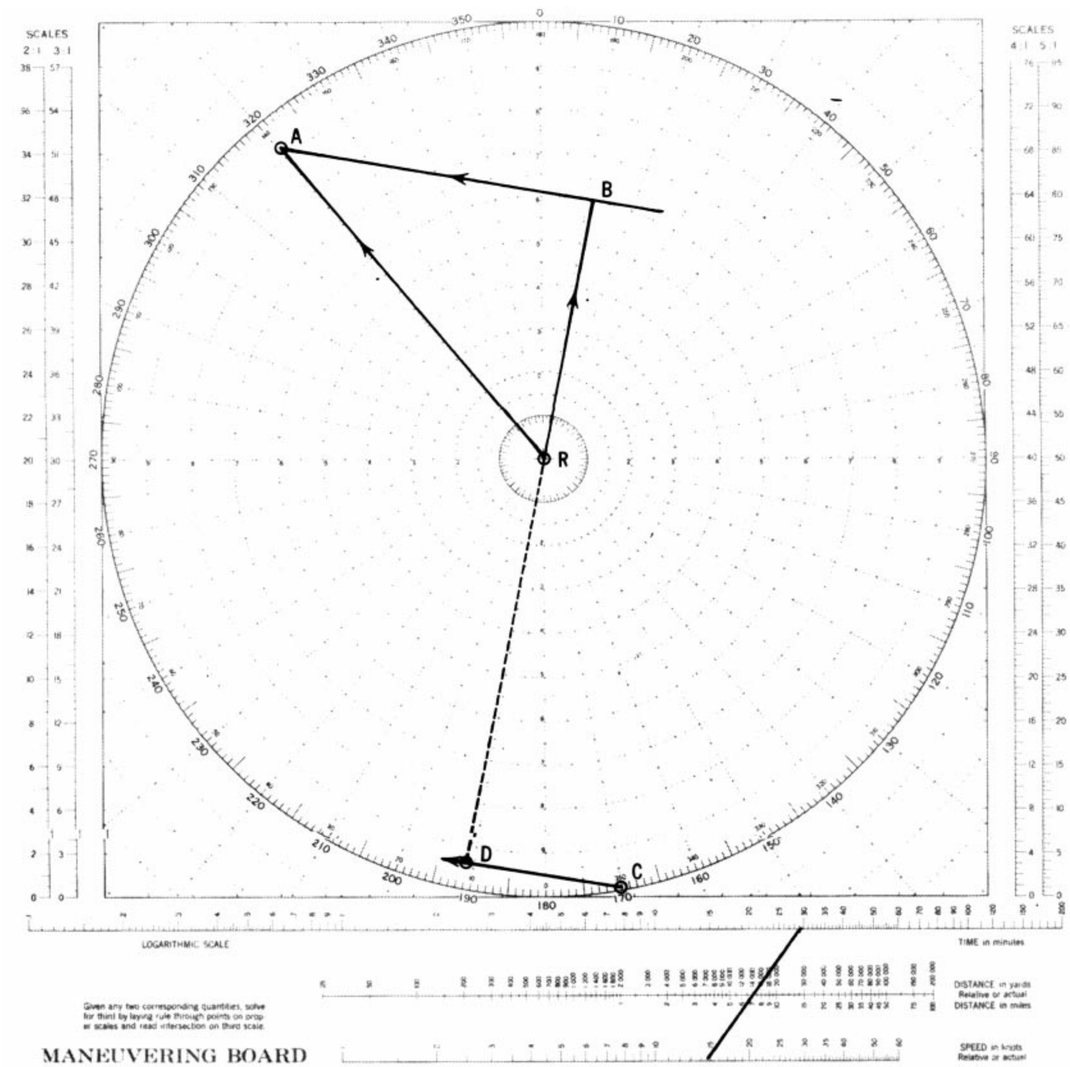


Figure 3611. Determining the course to avoid the storm center.

Southern Hemisphere

Left or dangerous semicircle: Bring the wind on the port bow (315° relative), hold course and make as much way as possible. If necessary, heave to with head to the sea.

Right or less dangerous semicircle: Bring the wind on the port quarter (225° relative), hold course and make as much way as possible. If necessary, heave to with stern to the sea.

On storm track, ahead of center: Bring the wind about 200° relative, hold course and make as much way as possible. When well within the less dangerous semicircle, maneuver as indicated above.

On storm track, behind center: Avoid the center by the best practicable course, keeping in mind the tendency of tropical cyclones to curve southward and eastward.

It is possible, particularly in temperate latitudes after the storm has recurved, that the dangerous semicircle is the left one in the Northern Hemisphere (right one in the Southern Hemisphere). This can occur if a large high lies north of the storm and causes a tightening of the pressure gradient in the region.

The *Typhoon Havens Handbook* for the Western Pacific and Indian Oceans is published by the Naval Oceanographic and Atmospheric Research Lab (NOARL) Monterey, California, as an aid to captains and commanding officers of ships in evaluating a typhoon situation, and to assist them in deciding whether to sortie, to evade, to remain in port, or to head for the shelter of a specific harbor.

CONSEQUENCES OF TROPICAL CYCLONES

3612. High Winds And Flooding

The high winds of a tropical cyclone inflict widespread damage when such a storm leaves the ocean and crosses land. Aids to navigation may be blown out of position or destroyed. Craft in harbors, often lifted by the storm surge, break moorings or drag anchor and are blown ashore and against obstructions. Ashore, trees are blown over, houses are damaged, power lines are blown down, etc. The greatest damage usually occurs in the dangerous semicircle a short distance from the center, where the strongest winds occur. As the storm continues on across land, its fury subsides faster than it would if it had remained over water.

Wind instruments are usually incapable of measuring the 175 to 200 knot winds of the more intense hurricanes; if the instrument holds up, often the supporting structure gives way. Doppler radar may be effective in determining wind speeds, but may also be blown away.

Wind gusts, which are usually 30 to 50 percent higher than sustained winds, add significantly to the destructiveness of the tropical cyclone. Many tropical cyclones that reach hurricane intensity develop winds of more than 90 knots sometime during their lives, but few develop winds of more than 130 knots.

Tropical cyclones have produced some of the world's heaviest rainfalls. While average amounts range from 6 to 10 inches, totals near 100 inches over a 4-day period have been observed. A 24-hour world's record of 73.62 inches fell at Reunion Island during a tropical cyclone in 1952. Forward movement of the storm and land topography have a considerable influence on rainfall totals. Torrential rains can occur when a storm moves against a mountain range; this is common in the Philippines and Japan, where even weak tropical depressions produce considerable rainfall. A 24-hour total of 46 inches was recorded in the Philippines during a typhoon in 1911. As hurricane Camille crossed southern Virginia's Blue Ridge Mountains in August of 1969, there was nearly 30 inches of rain in about 8 hours. This caused some of the most disastrous floods in the state's history.

Flooding is an extremely destructive by-product of the tropical cyclone's torrential rains. Whether an area will be flooded depends on the physical characteristics of the drainage basin, rate and accumulation of precipitation, and river stages at the time the rains begin. When heavy rains fall over flat terrain, the countryside may lie under water for a month or so, and while buildings, furnishings, and underground power lines may be damaged, there are usually few fatalities. In mountainous or hill country, disastrous floods develop rapidly and can cause a great loss of life.

There have been occasional reports in tropical cyclones of waves greater than 40 feet in height, and numerous reports in the 30- to 40-foot category. However, in tropical cyclones, strong winds rarely persist for a sufficiently long time or over a large enough area to permit enormous wave heights to develop. The direction and speed of the wind changes more rapidly in tropical cyclones than in extratropical storms. Thus, the maximum duration and fetch for any wind condition is often less in tropical cyclones than in extratropical storms, and the waves accompanying any given local wind conditions are generally not so high as those expected, with similar local wind conditions, in the high-latitude storms. In hurricane Camille, significant waves of 43 feet were recorded; an extreme wave height reached 72 feet.

Exceptional conditions may arise when waves of certain dimensions travel within the storm at a speed equal to the storm's speed, thus, in effect, extending the duration and fetch of the wave and significantly increasing its height. This occurs most often to the right of the track in the Northern Hemisphere (left of the track in the Southern Hemisphere). Another condition that may give rise to exceptional wave heights is the intersection of waves from

two or more distinct directions. This may lead to a zone of confused seas in which the heights of some waves will equal the sums of each individual wave train. This process can occur in any quadrant of the storm, so it should not be assumed that the highest waves will always be encountered to the right of the storm track in the Northern Hemisphere (left of the track in the Southern Hemisphere).

When these waves move beyond the influence of the generating winds, they become known as **swell**. They are recognized by their smooth, undulating form, in contrast to the steep, ragged crests of wind waves. This swell, particularly that generated by the right side of the storm, can travel a thousand miles or more and may produce tides 3 or 4 feet above normal along several hundred miles of coastline. It may also produce tremendous surf over offshore reefs which normally are calm.

When a tropical cyclone moves close to a coast, wind often causes a rapid rise in water level, and along with the falling pressure may produce a **storm surge**. This surge is usually confined to the right of the track in the Northern Hemisphere (left of the track in the Southern Hemisphere) and to a relatively small section of the coastline. It most often occurs with the approach of the storm, but in some cases, where a surge moves into a long channel, the effect may be delayed. Occasionally, the greatest rise in water is observed on the opposite side of the track, when northerly winds funnel into a partially landlocked harbor. The surge could be 3 feet or less, or it could be 20 feet or more, depending on the combination of factors involved.

There have been reports of a “hurricane wave,” described as a “wall of water,” which moves rapidly toward the coastline. Authenticated cases are rare, but some of the world’s greatest natural disasters have occurred as a result of this wave, which may be a rapidly rising and abnormally high storm surge. In India, such a disaster occurred in 1876, between Calcutta and Chittagong, and drowned more than 100,000 persons.

Along the coast, greater damage may be inflicted by water than by the wind. There are at least four sources of water damage. First, the unusually high seas generated by the storm winds pound against shore installations and craft in their way. Second, the continued blowing of the wind toward land causes the water level to increase perhaps 3 to 10 feet above its normal level. This **storm tide**, which may begin when the storm center is 500 miles or even farther from the shore, gradually increases until the storm passes. The highest storm tides are caused by a slow-moving tropical cyclone of large diameter, because both of these effects result in greater duration of wind in the same direction. The effect is greatest in a partly enclosed body of water, such as the Gulf of Mexico, where the concave coastline does not readily permit the escape of water. It is least on small islands, which present little obstruction to the flow of water. Third, the furious winds which blow around the wall of the eye create a ridge of water called a **storm wave**, which strikes the coast and often inflicts heavy damage. The effect is similar to that of a seismic sea wave, caused by an earthquake in the ocean floor. Both of these waves are popularly called **tidal waves**. Storm waves of 20 feet or more have occurred. About 3 or 4 feet of this wave is due to the decrease of atmospheric pressure, and the rest to winds. Like the damage caused by wind, damage due to high seas, the storm surge and tide, and the storm wave is greatest in the dangerous semicircle, near the center. The fourth source of water damage is the heavy rain that accompanies a tropical cyclone. This causes floods that add to the damage caused in other ways.

There have been many instances of tornadoes occurring within the circulation of tropical cyclones. Most of these have been associated with tropical cyclones of the North Atlantic Ocean and have occurred in the West Indies and along the gulf and Atlantic coasts of the United States. They are usually observed in the forward semicircle or along the advancing periphery of the storm. These tornadoes are usually short-lived and less intense than those that occur in the midwestern United States.

When proceeding along a shore recently visited by a tropical cyclone, a navigator should remember that time is required to restore aids to navigation which have been blown out of position or destroyed. In some instances the aid may remain but its light, sound apparatus, or radiobeacon may be inoperative. Landmarks may have been damaged or destroyed, and in some instances the coastline and hydrography may be changed.

CHAPTER 37

WEATHER OBSERVATIONS

BASICS OF WEATHER OBSERVATIONS

3700. Introduction

Weather forecasts are generally based upon information acquired by observations made at a large number of stations. Ashore, these stations are located so as to provide adequate coverage of the area of interest. Most observations at sea are made by mariners, wherever they happen to be. Since the number of observations at sea is small compared to the number ashore, marine observations are of great importance. Data recorded by designated vessels are sent by radio to weather centers ashore, where they are plotted, along with other observations, to provide data for drawing synoptic charts, which are used to make forecasts. Complete weather information gathered at sea by cooperating vessels is mailed to the appropriate meteorological services for use in the preparation of weather atlases and in marine climatological studies.

A special effort should be made to provide routine synoptic reports when transiting areas where few ships are available to report weather observations. This effort is particularly important in the tropics, where a vessel's synoptic weather report may be one of the first indications of a developing tropical cyclone. Even with satellite imagery, actual reports are needed to confirm suspicious patterns and provide actual temperature, pressure, and other measurements. Forecasts can be no better than the data received.

3701. Atmospheric Pressure

The sea of air surrounding the earth exerts a pressure of about 14.7 pounds per square inch on the surface of the earth. This **atmospheric pressure**, sometimes called **barometric pressure**, varies from place to place, and at the same place it varies over time.

Atmospheric pressure is one of the most basic elements of a meteorological observation. When the pressure at each station is plotted on a synoptic chart, lines of equal atmospheric pressure, called **isobars**, indicate the areas of high and low pressure. These are useful in making weather predictions, because certain types of weather are characteristic of each type of area, and the wind patterns over large areas can be deduced from the isobars.

Atmospheric pressure is measured with a **barometer**. A **mercurial barometer** measures pressure by balancing the weight of a column of air against that of a column of mercury. The **aneroid barometer** has a partly evacuated, thin metal cell which is compressed by atmospheric pressure; slight changes in air pressure cause the cell to expand or contract, while a system of levers magnifies and converts this motion to a reading on a gage or recorder.

Early mercurial barometers were calibrated to indicate the height, usually in inches or millimeters, of the column of mercury needed to balance the column of air above the point of measurement. While units of inches and millimeters are still widely used, many modern barometers are calibrated to indicate the centimeter-gram-second unit of pressure, the **millibar**, which is equal to 1,000 dynes per square centimeter. A dyne is the force required to accelerate a mass of one gram at the rate of one centimeter per second per second. A reading in any of the three units of measurement can be converted to the equivalent reading in either of the other units by means of tables, or the conversion factors given in the appendix. However, the pressure reading should always be reported in millibars.

3702. The Barometer

The **mercurial barometer** was invented by Evangelista Torricelli in 1643. In its simplest form it consists of a glass tube a little more than 30 inches in length and of uniform internal diameter. With one end closed, the tube is filled with mercury, and inverted into a cup of mercury. The mercury in the tube falls until the column is just supported by the pressure of the atmosphere on the open cup, leaving a vacuum at the upper end of the tube. The height of the column indicates atmospheric pressure, greater pressures supporting higher columns of mercury.

The mercurial barometer is subject to rapid variations in height, called **pumping**, due to pitch and roll of the vessel and temporary changes in atmospheric pressure in the vicinity of the barometer. Because of this, plus the care required in the reading the instrument, its bulkiness, and its vulnerability to physical damage, the mercurial barometer has been replaced at sea by the aneroid barometer.

3703. The Aneroid Barometer

The **aneroid barometer** measures the force exerted by atmospheric pressure on a partly evacuated, thin-metal element called a sylphon cell (aneroid capsule). A small spring is used, either internally or externally, to partly counteract the tendency of the atmospheric pressure to crush the cell.

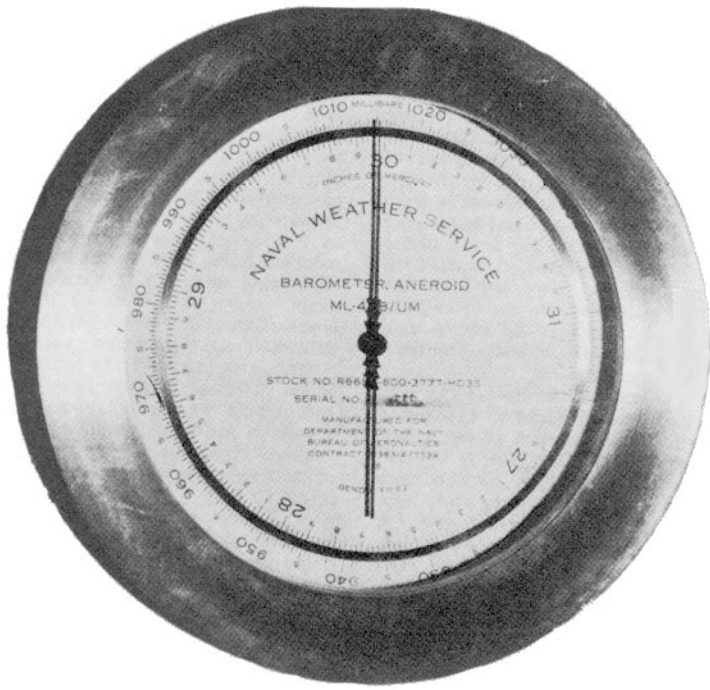


Figure 3703. An aneroid barometer.

Atmospheric pressure is indicated directly by a scale and a pointer connected to the cell by a combination of levers. The linkage provides considerable magnification of the slight motion of the cell, to permit readings to higher precision than could be obtained without it.

An aneroid barometer should be mounted permanently. Prior to installation, the barometer should be carefully set. U.S. ships of the Voluntary Observing Ship (VOS) program are set to sea level pressure. Other vessels may be set to station pressure and corrected for height as necessary. An adjustment screw is provided for this purpose. The error of the instrument is determined by comparison with a mercurial barometer or a standard precision aneroid barometer. If a qualified meteorologist is not available to make this adjustment, adjust by first removing only one-half the apparent error. The tap the case gently to assist the linkage to adjust itself, and repeat the adjustment. If the remaining error is not more than half a millibar (0.015 inch), no attempt should be made to remove it by further adjustment. Instead, a correction should be applied to the readings. The accuracy of this correction should be checked from time to time.

3704. The Barograph

The **barograph** is a recording barometer. In principle it is the same as a nonrecording aneroid barometer except that the pointer carries a pen at its outer end, and the scale is replaced by a slowly rotating cylinder around which a chart is wrapped. A clock mechanism inside the cylinder rotates the cylinder so that a continuous line is traced on the chart to indicate the pressure at any time.

The barograph is usually mounted on a shelf or desk in a room open to the atmosphere, in a location which minimizes the effect of the ship's vibration. Shock-absorbing material such as sponge rubber may be placed under the instrument to minimize vibration.

The pen should be checked and the inkwell filled each time the chart is changed.

A **marine microbarograph** is a precision barograph using greater magnification and an expanded chart. It is designed to maintain its precision through the conditions encountered aboard ship. Two sylphon cells are used, one mounted over the other in tandem. Minor fluctuations due to shocks or vibrations are eliminated by damping. Since oil-filled dashpots are used for this purpose, the instrument should never be inverted. The dashpots of the microbarograph should be kept filled with dashpot oil to within three-eighths inch of the top.

Ship motions are compensated by damping and spring loading which make it possible for the microbarograph to be tilted up to 22° without varying more than 0.3 millibars from true reading. Microbarographs have been almost entirely replaced by standard barographs.

Both instruments require checking from time to time to insure correct indication of pressure. The position of the pen is adjusted by a small knob provided for this purpose. The adjustment should be made in stages, eliminating half the apparent error, tapping the case to insure linkage adjustment to the new setting, and then repeating the process.

3705. Adjusting Barometer Readings

Atmospheric pressure as indicated by a barometer or barograph may be subject to several errors.

Instrument error: Inaccuracy due to imperfection or incorrect adjustment can be determined by comparison with a standard precision instrument. The National Weather Service provides a comparison service. In major U. S. ports a Port Meteorological Officer carries a portable precision aneroid barometer for barometer comparisons on board ships which participate in the Voluntary Observing Ship (VOS) program of the National Weather Service. The portable barometer is compared with station barometers before and after a ship visit. If a barometer is taken to a National Weather Service shore station, the comparison can be made there. The correct sea-level pressure can also be obtained by telephone. The shipboard barometer should be corrected for height, as explained below, before comparison with this value. If there is reason to believe that the barometer is in error, it should be compared with a standard, and if an error is found, the barometer should be adjusted to the correct reading, or a correction applied to all readings.

Height error: The atmospheric pressure reading at the height of the barometer is called the **station pressure** and is subject to a height correction in order to make it a sea level pressure reading. Isobars adequately reflect wind conditions and geographic distribution of pressure only when they are drawn for pressure at constant height (or the varying height at which a constant pressure exists). On synoptic charts it is customary to show the equivalent pressure at sea level, called **sea level pressure**. This is found by applying a correction to station pressure. The correction depends upon the height of the barometer and the average temperature of the air between this height and the surface. The outside air temperature taken aboard ship is sufficiently accurate for this purpose. This is an important correction which should be applied to all readings of any type barometer. See Table 31 for this correction.

Gravity error: Mercurial barometers are calibrated for standard sea-level gravity at latitude 45°32'40". If the gravity differs from this amount, an error is introduced. The correction to be applied to readings at various latitudes is given in Table 32. This correction does not apply to readings of an aneroid barometer or microbarograph. Gravity also changes with height above sea level, but the effect is negligible for the first few hundred feet, and so is not needed for readings taken aboard ship. See Table 32 for this correction.

Temperature error: Barometers are calibrated at a standard temperature of 32°F. The liquid of a mercurial barometer expands as the temperature of the mercury rises, and contracts as it decreases. The correction to adjust the reading of the instrument to the true value is given in Table 33. This correction is applied to readings of mercurial barometers only. Modern aneroid barometers are compensated for temperature changes by the use of different metals having unequal coefficients of linear expansion.

3706. Temperature

Temperature is a measure of heat energy, measured in degrees. Several different temperature scales are in use.

On the **Fahrenheit (F)** scale pure water freezes at 32° and boils at 212°.

On the **Celsius (C)** scale commonly used with the metric system, the freezing point of pure water is 0° and the boiling point is 100°. This scale, has been known by various names in different countries. In the United States it was formerly called the centigrade scale. The Ninth General Conference of Weights and Measures, held in France in 1948, adopted the name Celsius to be consistent with the naming of other temperature scales after their inventors, and to avoid the use of different names in different countries. On the original Celsius scale, invented in 1742 by a Swedish astronomer named Anders Celsius, numbering was the reverse of the modern scale, 0° representing the boiling point of water, and 100° its freezing point.

Absolute zero is considered to be the lowest possible temperature, at which there is no molecular motion and a body has no heat. For some purposes, it is convenient to express temperature by a scale at which 0° is absolute zero. This is called **absolute temperature**. If Fahrenheit degrees are used, it may be called **Rankine (R)** temperature; and if Celsius, **Kelvin (K)** temperature. The Kelvin scale is more widely used than the Rankine. Absolute zero is –459.69°F or –273.16°C.

Temperature of one scale can be easily converted to another because of the linear mathematical relationship between them. Note that the sequence of calculation is slightly different; algebraic rules must be followed.

$$C = \frac{5}{9}(F - 32), \text{ or } \qquad C = \frac{F - 32}{1.8}$$

$$F = \frac{9}{5}C + 32, \text{ or } \qquad F = 1.8C + 32$$

$$K = C + 273.16$$

$$R = F + 459.69$$

A temperature of –40° is the same by either the Celsius or Fahrenheit scale. Similar formulas can be made for conversion of other temperature scale readings. The Conversion Table for Thermometer Scales (Table 29) gives the equivalent values of Fahrenheit, Celsius, and Kelvin temperatures.

The intensity or degree of heat (temperature) should not be confused with the amount of heat. If the temperature of air or some other substance is to be increased (the substance made hotter) by a given number of degrees, the amount of heat that must be added is dependent upon the amount of the substance to be heated. Also, equal amounts of different substances require the addition of unequal amounts of heat to effect an equal increase in temperature because of their difference of specific heat. Units used for measurement of amount of heat are the **British thermal unit (BTU)**, the amount of heat needed to

raise the temperature of 1 pound of water 1° Fahrenheit; and the **calorie**, the amount of heat needed to raise the temperature of 1 gram of water 1° Celsius.

3707. Temperature Measurement

Temperature is measured with a **thermometer**. Most thermometers are based upon the principle that materials expand with an increase of temperature, and contract as temperature decreases. In its most usual form a thermometer consists of a bulb filled with mercury and connected to a tube of very small cross-sectional area. The mercury only partly fills the tube. In the remainder is a vacuum. Air is driven out by boiling the mercury, and the top of the tube is then sealed. As the mercury expands or contracts with changing temperature, the length of the mercury column in the tube changes.

Sea surface temperature observations are used in the forecasting of fog and furnish important information about the development and movement of tropical cyclones. Commercial fishermen are interested in the sea surface temperature as an aid in locating certain species of fish. There are several methods of determining seawater temperature. These include engine room intake readings, condenser intake readings, thermistor probes attached to the hull, and readings from buckets recovered from over the side. Although the condenser intake method is not a true measure of surface water temperature, the error is generally small.

If the surface temperature is desired, a sample should be obtained by bucket, preferably a canvas bucket, from a forward position well clear of any discharge lines. The sample should be taken immediately to a place where it is sheltered from wind and sun. The water should then be stirred with the thermometer, keeping the bulb submerged, until a constant reading is obtained.

A considerable variation in sea surface temperature can be experienced in a relatively short distance of travel. This is especially true when crossing major ocean currents such as the Gulf Stream and the Kuroshio Current. Significant variations also occur where large quantities of freshwater are discharged from rivers. A clever navigator will note these changes as in indication of when to allow for set and drift in dead reckoning.

3708. Humidity

Humidity is a measure of the atmosphere's water vapor content. **Relative humidity** is the ratio, stated as a percentage, of the pressure of water vapor present in the atmosphere to the saturation vapor pressure at the same temperature.

As air temperature decreases, the relative humidity increases. At some point, saturation takes place, and any further cooling results in condensation of some of the moisture. The temperature at which this occurs is called the dew point, and the moisture deposited upon objects is called dew if it forms in the liquid state, or frost if it forms in the frozen state.

The same process causes moisture to form on the outside of a container of cold liquid, the liquid cooling the air in the immediate vicinity of the container until it reaches the dew point. When moisture is deposited on man-made objects, it is usually called **sweat**. It occurs whenever the temperature of a surface is lower than the dew point of air in contact with it. It is of particular concern to the mariner because of its effect upon his instruments, and possible damage to his ship or its cargo. Lenses of optical instruments may sweat, usually with such small droplets that the surface has a "frosted" appearance. When this occurs, the instrument is said to "fog" or "fog up," and is useless until the moisture is removed. Damage is often caused by corrosion or direct water damage when pipes sweat and drip, or when the inside of the shell plates of a vessel sweat. Cargo may sweat if it is cooler than the dew point of the air.

Clouds and fog form from condensation of water on minute particles of dust, salt, and other material in the air. Each particle forms a nucleus around which a droplet of water forms. If air is completely free from solid particles on which water vapor may condense, the extra moisture remains in the vapor state, and the air is said to be **supersaturated**.

Relative humidity and dew point are measured with a **hygrometer**. The most common type, called a **psychrometer**, consists of two thermometers mounted together on a single strip of material. One of the thermometers is mounted a little lower than the other, and has its bulb covered with muslin. When the muslin covering is thoroughly moistened and the thermometer well ventilated, evaporation cools the bulb of the thermometer, causing it to indicate a lower reading than the other. A **sling psychrometer** is ventilated by whirling the thermometers. The difference between the dry-bulb and wet-bulb temperatures is used to enter **psychrometric tables** (Table 35 and Table 36) to find the relative humidity and dew point. If the wet-bulb temperature is above freezing, reasonably accurate results can be obtained by a psychrometer consisting of dry- and wet-bulb thermometers mounted so that air can circulate freely around them without special ventilation. This type of installation is common aboard ship.

Example: *The dry-bulb temperature is 65°F, and the wet-bulb temperature is 61°F.*

Required: *(1) Relative humidity, (2) dew point.*

Solution: *The difference between readings is 4°. Entering Table 35 with this value, and a dry-bulb temperature of 65°, the relative humidity is found to be 80 percent. From Table 36 the dew point is 58°.*

Answers: *(1) Relative humidity 80 percent, (2) dew point 58°.*

Also in use aboard many ships is the **electric psychrometer**. This is a hand held, battery operated instrument with two mercury thermometers for obtaining dry- and wet-bulb temperature readings. It consists of a plastic housing that holds the thermometers, batteries, motor, and fan.

3709. Wind Measurement

Wind measurement consists of determination of the direction and speed of the wind. Direction is measured by a **wind vane**, and speed by an **anemometer**.

Several types of wind speed and direction sensors are available, using vanes to indicate wind direction and rotating cups or propellers for speed sensing. Many ships have reliable wind instruments installed, and inexpensive wind instruments are available for even the smallest yacht. If no anemometer is available, wind speed can be estimated by its effect upon the sea and nearby objects. The direction can be computed accurately, even on a fast moving vessel, by maneuvering board or Table 30.

3710. True And Apparent Wind

An observer aboard a vessel proceeding through still air experiences an apparent wind which is from dead ahead and has an apparent speed equal to the speed of the vessel. Thus, if the actual or true wind is zero and the speed of the vessel is 10 knots, the apparent wind is from dead ahead at 10 knots. If the true wind is from dead ahead at 15 knots, and the speed of the vessel is 10 knots, the apparent wind is 15 + 10 = 25 knots from dead ahead. If the vessel reverses course, the apparent wind is 15 – 10 = 5 knots, from dead astern.

The **apparent wind** is the vector sum of the true wind and the *reciprocal* of the vessel's course and speed vector. Since wind vanes and anemometers measure apparent wind, the usual problem aboard a vessel equipped with an anemometer is to convert apparent wind to true wind. There are several ways of doing this. Perhaps the simplest is by the graphical solution illustrated in the following example:

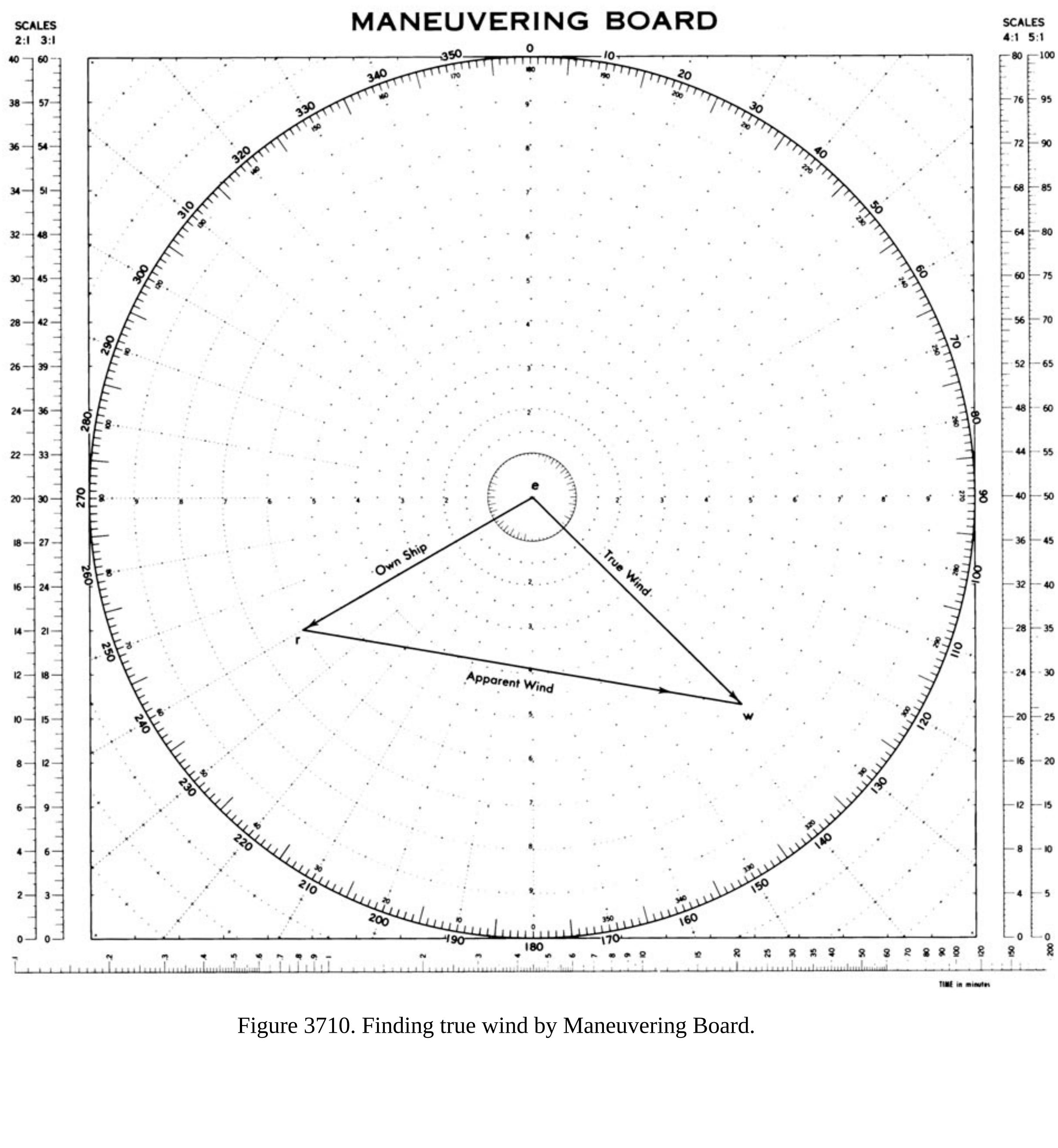


Figure 3710. Finding true wind by Maneuvering Board.

Example 1: *A ship is proceeding on course 240° at a speed of 18 knots. The apparent wind is from 040° relative at 30 knots.*

Required: *The direction and speed of the true wind.*

Solution: *First starting from the center of a maneuvering board, plot the ship's vector er, at 240°, length 18 knots (using the 3–1 scale). Next plot the relative wind's vector from r, in a direction of 100° (the reciprocal of 280°) length 30 knots. The true wind is from the center to the end of this vector or line ew.*

Alternatively, you can plot the ship's vector from the center, then plot the relative wind's vector toward the center, and see the true wind's vector from the end of this line to the end of the ship's vector. Use parallel rulers to transfer the wind vector to the center for an accurate reading.

Answer: *True wind is from 315° at 20 knots.*

On a moving ship, the direction of the true wind is always on the same side and aft of the direction of the apparent wind. The faster the ship moves, the more the apparent wind draws ahead of the true wind.

Solution can also be made without plotting, in the following manner: On a maneuvering board, label the circles 5, 10, 15, 20, etc., from the center, and draw vertical lines tangent to these circles. Cut out the 5:1 scale and discard that part having graduations greater than the maximum speed of the vessel. Keep this sheet for all solutions. (For durability, the two parts can be mounted on cardboard or other suitable material.) To find true wind, spot in point 1 by eye. Place the zero of the 5:1 scale on this point and align the scale (inverted) using the vertical lines. Locate point 2 at the speed of the vessel as indicated on the 5:1 scale. It is always vertically below point 1. Read the relative direction and the speed of the true wind, using eye interpolation if needed.

A tabular solution can be made using Table 30, Direction and Speed of True Wind in Units of Ship's Speed. The entering values for this table are the apparent wind speed in units of ship's speed, and the difference between the heading and the apparent wind direction. The values taken from the table are the relative direction (right or left) of the true wind, and the speed of the true wind in units of ship's speed. If a vessel is proceeding at 12 knots, 6 knots constitutes one-half (0.5) unit, 12 knots one unit, 18 knots 1.5 units, 24 knots two units, etc.

Example 2: *A ship is proceeding on course 270° at a speed of 10 knots. The apparent wind is from 10° off the port bow, speed 30 knots.*

Required: *The relative direction, true direction, and speed of the true wind by table.*

Solution: *The apparent wind speed is*

$$\frac{30}{10} = 3.0 \text{ ships speed units}$$

Enter Table 30 with 3.0 and 10° and find the relative direction of the true wind to be 15° off the port bow (345° relative), and the speed to be 2.02 times the ship's speed, or 20 knots, approximately. The true direction is 345° + 270° = 255°.

Answers: *True wind from 345° relative = 255° true, at 20 knots.*

By variations of this problem, one can find the apparent wind from the true wind, the course or speed required to produce an apparent wind from a given direction or speed, or the course and speed to produce an apparent wind of a given speed from a given direction. Such problems often arise in aircraft carrier operations and in some rescue situations. See *Pub. 217, Maneuvering Board Manual*, for more detailed information.

When wind speed and direction are determined by the appearance of the sea, the result is true speed and direction. Waves move in the same direction as the generating wind, and are not deflected by earth's rotation. If a wind vane is used, the direction of the apparent wind thus determined can be used with the speed of the true wind to determine the direction of the true wind by vector diagram.

WIND AND WAVES

3711. Effects Of Wind On The Sea

There is a direct relationship between the speed of the wind and the state of the sea. This is useful in predicting the sea conditions to be anticipated when future wind speed forecasts are available. It can also be used to estimate the speed of the wind, which may be necessary when an anemometer is not available.

Wind speeds are usually grouped in accordance with the Beaufort scale, named after Admiral Sir Francis Beaufort (1774-1857), who devised it in 1806. As adopted in 1838, Beaufort numbers ranged from 0 (calm) to 12 (hurricane). The Beaufort wind scale and sea state photographs which are at the end of this chapter can be used to estimate wind speed.

These pictures *(courtesy of Environment Canada)* present the results of a project carried out on board the Canadian Ocean Weather Ships VANCOUVER and QUADRA at Ocean Weather Station PAPA (50°N., 145°W), between April 1976 and May 1981. The aim of the project was to collect color photographs of the sea surface as it appears under the influence of the various ranges of wind speed, as defined by The Beaufort Scale of Wind Force. The photographs represent as closely as possible steady-state sea conditions over many hours for each Beau-

fort wind force, except Force 12, for which no photographs are available. They were taken from heights ranging from 12-17 meters above the sea surface; anemometer height was 28 meters.

3712. Estimating The Wind At Sea

Observers on board ships at sea usually determine the speed of the wind by estimating Beaufort Force, as merchant ships may not be equipped with wind measuring instruments. Through experience, ships' officers have developed various methods of estimating this force. The effect of the wind on the observer himself, the ship's rigging, flags, etc., is used as a guide, but estimates based on these indications give the relative wind which must be corrected for the motion of the ship before an estimate of the true wind speed can be obtained.

The most common method involves the appearance of the sea surface. The state of the sea disturbance, i.e. the dimensions of the waves, the presence of white caps, foam, or spray, depends principally on three factors:

1. **The wind speed**. The higher the speed of the wind, the greater is the sea disturbance.
2. **The wind's duration**. At any point on the sea, the disturbance will increase the longer the wind blows at a given speed, until a maximum state of disturbance is reached.
3. **The fetch**. This is the length of the stretch of water over which the wind acts on the sea surface from the same direction.

For a given wind speed and duration, the longer the fetch, the greater is the sea disturbance. If the fetch is short, such as a few miles, the disturbance will be relatively small no matter how great the wind speed is or how long it has been blowing.

There are other factors which can modify the appearance of the sea surface caused by wind alone. These are strong currents, shallow water, swell, precipitation, ice, and wind shifts. Their effects will be described later.

A wind of a given Beaufort Force will, therefore, produce a characteristic appearance of the sea surface provided that it has been blowing for a sufficient length of time, and over a sufficiently long fetch.

In practice, the mariner observes the sea surface, noting the size of the waves, the white caps, spindrift, etc., and then finds the criterion which best describes the sea surface as he saw it. This criterion is associated with a Beaufort number, for which a corresponding mean wind speed and range in knots are given. Since meteorological reports require that wind speeds be reported in knots, the mean speed for the Beaufort number may be reported, or an experienced observer may judge that the sea disturbance is such that a higher or lower speed within the range for the force is more accurate.

This method should be used with caution. The sea conditions described for each Beaufort Force are "steady-state" conditions; i.e. the conditions which result when the wind has been blowing for a relatively long time, and over a great stretch of water. At any particular time at sea, though, the duration of the wind or the fetch, or both, may not have been great enough to produce these "steady-state" conditions. When a high wind springs up suddenly after previously calm or near calm conditions, it will require some hours, depending on the strength of the wind, to generate waves of maximum height. The height of the waves increases rapidly in the first few hours after the commencement of the blow, but increases at a much slower rate later on.

At the beginning of the fetch (such as at a coastline when the wind is offshore) after the wind has been blowing

Beaufort force of wind.	Theoretical maximum wave height (ft) unlimited duration and fetch.	Duration of winds, (hours), with unlimited fetch, to produce percent of maximum wave height indicated.			Fetch (nautical miles), with unlimited duration of blow, to produce percent of maximum wave height indicated.		
		50%	75%	90%	50%	75%	90%
3	2	1.5	5	8	3	13	25
5	8	3.5	8	12	10	30	60
7	20	5.5	12	21	22	75	150
9	40	7	16	25	55	150	280
11	70	9	19	32	85	200	450

Table 3712. Duration of winds and length of fetches required for various wind forces.

for a long time, the waves are quite small near shore, and increase in height rapidly over the first 50 miles or so of the fetch. Farther offshore, the rate of increase in height with distance slows down, and after 500 miles or so from the beginning of the fetch, there is little or no increase in height.

Table 3712 illustrates the duration of winds and the length of fetches required for various wind forces to build seas to 50 percent, 75 percent, and 90 percent of their theoretical maximum heights.

The theoretical maximum wave heights represent the average heights of the highest third of the waves, as these waves are most significant.

It will be seen that winds of force 5 or less can build seas to 90 percent of their maximum height, in less than 12 hours, provided the fetch is long enough. Higher winds require a much greater time-force 11 winds requiring 32 hours to build waves to 90 percent of their maximum height. The times given in Table 3712 represent those required to build waves starting from initially calm sea conditions. If waves are already present at the onset of the blow, the times would be somewhat less depending on the initial wave heights and their direction relative to the direction of the wind which has sprung up.

The first consideration when using the sea criterion to estimate wind speed, therefore, is to decide whether the wind has been blowing long enough from the same direction to produce a steady state sea condition. If not, then it is possible that the wind speed may be underestimated.

Experience has shown that the appearance of white-caps, foam, spindrift, etc., reaches a steady state condition before the height of the waves attain their maximum value. It is a safe assumption that the appearance of the sea (such as white-caps, etc.) will reach a steady state in the time required to build the waves to 50-75 percent of their maximum height. Thus, from Table 3712, it is seen that a force 5 wind could require 8 hours at most to produce a characteristic appearance of the sea surface.

A second consideration, when using the sea criterion, is the length of the fetch over which the wind has been blowing to produce the present state of the sea. On the open sea, unless the mariner has the latest synoptic weather map available, the length of the fetch will not be known. It will be seen from Table 3712, though, that only relatively short fetches are required for the lower wind forces to generate their characteristic seas. On the open sea, the fetches associated with most storms and other weather systems are usually long enough so that even winds up to force 9 can build seas up to 90 percent or more of their maximum height, providing the wind blows from the same direction long enough.

When navigating close to a coast, or in restricted waters, however, it may be necessary to make allowances for the shorter stretches of water over which the wind blows. For example, referring to Table 3712, if the ship is 22 miles from a coast, and an offshore wind with an actual speed of force 7 is blowing, the waves at the ship will never attain more than 50 percent of their maximum height for this speed no matter how long the wind blows. Hence, if the sea criterion were used under these conditions without consideration of the short fetch, the wind speed would be underestimated. With an offshore wind, the sea criterion may be used with confidence if the distance to the coast is greater than the values given in the extreme right-hand column of Table 3712; again, provided that the wind has been blowing offshore for a sufficient length of time.

3713. Special Wind Effects

Tidal and Other Currents: A wind blowing against a tide or strong current causes a greater sea disturbance than normal, which may result in an overestimate of the wind speed. On the other hand, a wind blowing in the same direction as a tide or strong current causes less sea disturbance than normal, and may result in an underestimate of the wind speed.

Shallow Water: Waves running into shallow water increase in steepness, and hence, their tendency to break. With an onshore wind there will, therefore, be more white-caps over the shallow waters than over the deeper water farther offshore. It is only over relatively deep water that the sea criterion can be used with confidence.

Swell: Swell is the name given to waves, generally of considerable length, which were raised in some distant area by winds blowing there, and which have moved into the vicinity of the ship; or to waves raised nearby and which continue to advance after the wind at the ship has abated or changed direction. The direction of swell waves is usually different from the direction of the wind and the sea waves. Swell waves are not considered when estimating wind speed and direction. Only those waves raised by the wind blowing at the time are of any significance. The wind-driven waves show a greater tendency to break when superimposed on the crests of swell, and hence, more whitecaps may be formed than if the swell were absent. Under these conditions, the use of the sea criterion may result in a slight overestimate of the wind speed.

Precipitation: Heavy rain has a damping or smoothing effect on the sea surface which must be mechanical in character. Since the sea surface will therefore appear less disturbed than would be the case without the rain, the wind speed may be underestimated unless the smoothing effect is taken into account.

Ice: Even small concentrations of ice floating on the sea surface will dampen waves considerably, and concentrations greater than about seven-tenths average will eliminate waves altogether. Young sea ice, which in the early stages of formation has a thick soupy consistency, and later takes on a rubbery appearance, is very effective in dampening waves. Consequently, the sea criterion cannot be used with any degree of confidence when sea ice is present. In higher latitudes, the presence of an ice field some distance to windward of the ship may be suspected if, when the ship is not close to any coast, the wind is relatively strong but the seas abnormally underdeveloped. The edge of the ice field acts like a coastline, and the short fetch between the ice and the

ship is not sufficient for the wind to fully develop the seas.

Wind Shifts: Following a rapid change in the direction of the wind, as occurs at the passage of a cold front, the new wind will flatten out to a great extent the waves which were present before the wind shift. This happens because the direction of the wind after the shift may differ by 90° or more from the direction of the waves, which does not change. Hence, the wind may oppose the progress of the waves and dampen them out quickly. At the same time, the new wind begins to generate its own waves on top of this dissipating swell, and it is not long before the cross pattern of waves gives the sea a "choppy" or confused appearance. It is during the first few hours following the wind shift that the appearance of the sea surface may not provide a reliable indication of wind speed. The wind is normally stronger than the sea would indicate, as old waves are being flattened out, and new waves are beginning to be developed.

Night Observations: On a dark night, when it is impossible to see the sea clearly, the observer may estimate the apparent wind from its effect on the ship's rigging, flags, etc., or simply the "feel" of the wind.

CLOUDS

3714. Cloud Formation

Clouds consist of innumerable tiny droplets of water, or ice crystals, formed by condensation of water vapor around microscopic particles in the air. **Fog** is a cloud in contact with the surface of the earth.

The shape, size, height, thickness, and nature of a cloud depend upon the conditions under which it is formed. Therefore, clouds are indicators of various processes occurring in the atmosphere. The ability to recognize different types, and a knowledge of the conditions associated with them, are useful in predicting future weather.

Although the variety of clouds is virtually endless, they may be classified according to general type. Clouds are grouped generally into three "families" according to common characteristics. **High clouds** have a mean lower level above 20,000 feet. They are composed principally of ice crystals. **Middle clouds** have a mean level between 6,500 and 20,000 feet. They are composed largely of water droplets, although the higher ones have a tendency toward ice particles. **Low clouds** have a mean lower level of less than 6,500 feet. These clouds are composed entirely of water droplets.

Within these 3 families are 10 principal cloud types. The names of these are composed of various combinations and forms of the following basic words, all from Latin:

Cirrus, meaning "curl, lock, or tuft of hair."
Cumulus, meaning "heap, a pile, an accumulation."
Stratus, meaning "spread out, flatten, cover with a layer."
Alto, meaning "high, upper air."
Nimbus, meaning "rainy cloud."

Individual cloud types recognize certain characteristics, variations, or combinations of these. The 10 principal cloud types and their commonly used symbols are:

3715. High Clouds

Cirrus (Ci) are detached high clouds of delicate and fibrous appearance, without shading, generally white in color, and often of a silky appearance (Figure 3715a and Figure 3715d). Their fibrous and feathery appearance is caused by their composition of ice crystals. Cirrus appear in varied forms such as isolated tufts; long, thin lines across the sky; branching, feather-like plumes; curved wisps which may end in tufts, and other shapes. These clouds may be arranged in parallel bands which cross the sky in great circles, and appear to converge toward a point on the horizon. This may indicate the general direction of a low pressure area. Cirrus may be brilliantly colored at sunrise and sunset. Because of their height, they become illuminated before other clouds in the morning, and remain lighted after others at sunset. Cirrus are generally associated with fair weather, but if they are followed by lower and thicker clouds, they are often the forerunner of rain or snow.

Cirrocumulus (Cc) are high clouds composed of small white flakes or scales, or of very small globular masses, usually without shadows and arranged in groups of lines, or more often in ripples resembling sand on the seashore (Figure 3715b). One form of cirrocumulus is popularly known as "mackerel sky" because the pattern resembles the scales on the back of a mackerel. Like cirrus, cirrocumulus are composed of ice crystals and are generally associated with fair weather, but may precede a storm if they thicken and lower. They may turn gray and appear hard before thickening.

Cirrostratus (Cs) are thin, whitish, high clouds (Fig. 3715c) sometimes covering the sky completely and giving it a milky appearance and at other times presenting, more or less distinctly, a formation like a tangled web. The thin veil is not sufficiently dense to blur the outline of sun or moon. However, the ice crystals of which the cloud is composed refract the light passing through to form halos with the sun or moon at the center. Figure 3715d shows cirrus thickening and changing into cirrostratus. In this form it is popularly known as "mares' tails." If it continues to thicken and lower, the ice crystals melting to form water droplets, the cloud formation is known as altostratus. When this occurs, rain may normally be expected within 24 hours. The more brush-like the cirrus when the sky appears as in Figure 3715d, the stronger wind at the level of the cloud.

Figure 3715a. Cirrus.

Figure 3715b. Cirrocumulus.

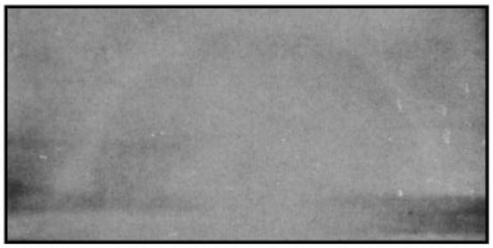


Figure 3715c. Cirrostratus.

Figure 3715d. Cirrus and cirrostratus.

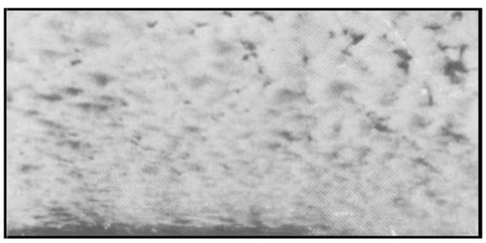


Figure 3716a. Altocumulus in patches.

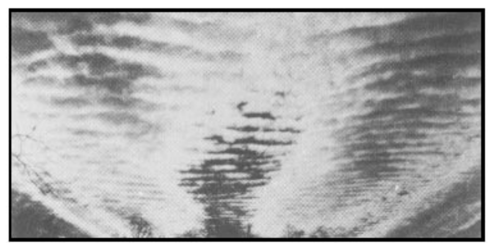


Figure 3716b. Altocumulus in bands.

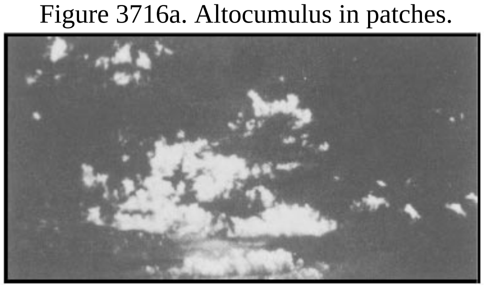


Figure 3716c. Turreted altocumulus.

Figure 3716d. Altostratus.

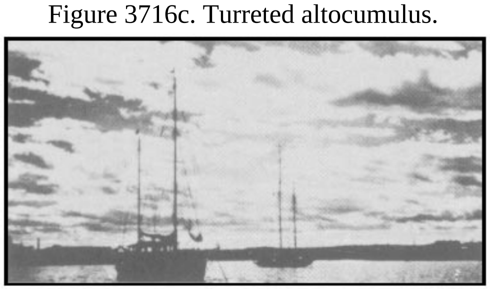


Figure 3717a. Stratocumulus.

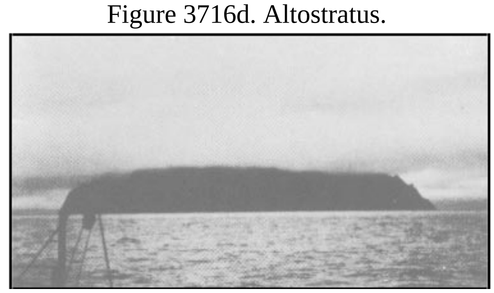


Figure 3717b. Stratus.

Figure 3717c. Cumulus.

Figure 3717d. Cumulonimbus.

3716. Middle Clouds

Altocumulus (Ac) are middle level clouds consisting of a layer of large, ball-like masses that tend to merge together. The balls or patches may vary in thickness and color from dazzling white to dark gray, but they are more or less regularly arranged. They may appear as distinct patches (Figure 3716a) similar to cirrocumulus, but can be distinguished by having individual patches which are generally larger, showing distinct shadows in some places. They are often mistaken for stratocumulus. If altocumulus thickens and lowers, it may produce thundery weather and showers, but it does not bring prolonged bad weather. Sometimes the patches merge to form a series of big rolls resembling ocean waves, with streaks of blue sky between (Figure 3716b). Because of perspective, the rolls appear to run together near the horizon. These regular parallel bands differ from cirrocumulus because they occur in larger masses with shadows. Altocumulus move in the direction of the short dimension of the rolls, like ocean waves. Sometimes altocumulus appear briefly in the form shown in Figure 3716c, usually before a thunderstorm. They are generally arranged in a line with a flat horizontal base, giving the impression of turrets on a castle. The turreted tops may look like miniature cumulus and possess considerable depth and great length. These clouds usually indicate a change to chaotic, thundery skies.

Altostratus (As) are middle clouds having the appearance of a grayish or bluish, fibrous veil or sheet (Figure 3716d). The sun or moon, when seen through these clouds, appears as if it were shining through ground glass, with a corona around it. Halos are not formed. If these clouds thicken and lower, or if low, ragged “scud” or rain clouds (nimbostratus) form below them, continuous rain or snow may be expected within a few hours.

3717. Low Clouds

Stratocumulus (Sc) are low clouds appearing as soft, gray, roll-shaped masses (Figure 3717a). They may be shaped in long, parallel rolls similar to altocumulus, moving forward with the wind. The motion is in the direction of their short dimension, like ocean waves. These clouds, which vary greatly in altitude, are the final product of the characteristic daily change taking place in cumulus clouds. They are usually followed by clear skies during the night.

Stratus (St) is a low cloud in a uniform layer (Figure 3717b) resembling fog. Often the base is not more than 1,000 feet high. A veil of thin stratus gives the sky a hazy appearance. Stratus is often quite thick, permitting so little sunlight to penetrate that it appears dark to an observer below. From above, it is white. Light mist may descend from stratus. Strong wind sometimes breaks stratus into shreds called “fractostratus.”

Nimbostratus (Ns) is a low, dark, shapeless cloud layer, usually nearly uniform, but sometimes with ragged, wet-looking bases. Nimbostratus is the typical rain cloud. The precipitation which falls from this cloud is steady or intermittent, but not showery.

Cumulus (Cu) are dense clouds with vertical development formed by rising air which is cooled as it reaches greater heights. See Figure 3717c. They have a horizontal base and dome-shaped upper surface, with protuberances extending above the dome. Cumulus appear in small patches, and never cover the entire sky. When the vertical development is not great, the clouds appear in patches resembling tufts of cotton or wool, being popularly called “woolpack” clouds. The horizontal bases of such clouds may not be noticeable. These are called “fair weather” cumulus because they commonly accompany good weather. However, they may merge with altocumulus, or may grow to cumulonimbus before a thunderstorm. Since cumulus are formed by updrafts, they are accompanied by turbulence, causing “bumpiness” in the air. The extent of turbulence is proportional to the vertical extent of the clouds. Cumulus are marked by strong contrasts of light and dark.

Cumulonimbus (Cb) is a massive cloud with great vertical development, rising in mountainous towers to great heights (Figure 3717d). The upper part consists of ice crystals, and often spreads out in the shape of an anvil which may be seen at such distances that the base may be below the horizon. Cumulonimbus often produces showers of rain, snow, or hail, frequently accompanied by lightning and thunder. Because of this, the cloud is often popularly called a “thundercloud” or “thunderhead.” The base is horizontal, but as showers occur it lowers and becomes ragged.

3718. Cloud Height Measurement

At sea, cloud heights are often determined by estimate. This is a difficult task, particularly at night.

The height of the base of clouds formed by vertical development (any form of cumulus), if formed in air that has risen from the surface of the earth, can be determined by psychrometer, because the height to which the air must rise before condensation takes place is proportional to the difference between surface air temperature and the dew point. At sea, this difference multiplied by 126.3 gives the height in meters. That is, for every degree difference between surface air temperature and the dew point, the air must rise 126.3 meters before condensation will take place. Thus, if the dry-bulb temperature is 26.8°C, and the wet-bulb temperature is 25.0°C, the dew point is 24°C, or 2.8°C lower than the surface air temperature. The height of the cloud base is $2.8 \times 126.3 = 354$ meters.

OTHER OBSERVATIONS

3719. Visibility Measurement

Visibility is the horizontal distance at which prominent objects can be seen and identified by the unaided eye. It is usually measured directly by the human eye. Ashore, the distances of various buildings, trees, lights, and other objects can be used as a guide in estimating the visibility. At sea, however, such an estimate is difficult to make with accuracy. Other ships and the horizon may be of some assistance. See Table 12, Distance of the Horizon.

Ashore, visibility is sometimes measured by a **transmissometer**, a device which measures the transparency of the atmosphere by passing a beam of light over a known short distance, and comparing it with a reference light.

3720. Upper Air Observations

Upper air information provides the third dimension to the weather map. Unfortunately, the equipment necessary to obtain such information is quite expensive, and the observations are time consuming. Consequently, the network of observing stations is quite sparse compared to that for surface observations, particularly over the oceans and in isolated land areas. Where facilities exist, upper air observations are made by means of unmanned balloons, in conjunction with theodolites, radiosondes, radar, and radio direction finders.

3721. New Technologies In Weather Observing

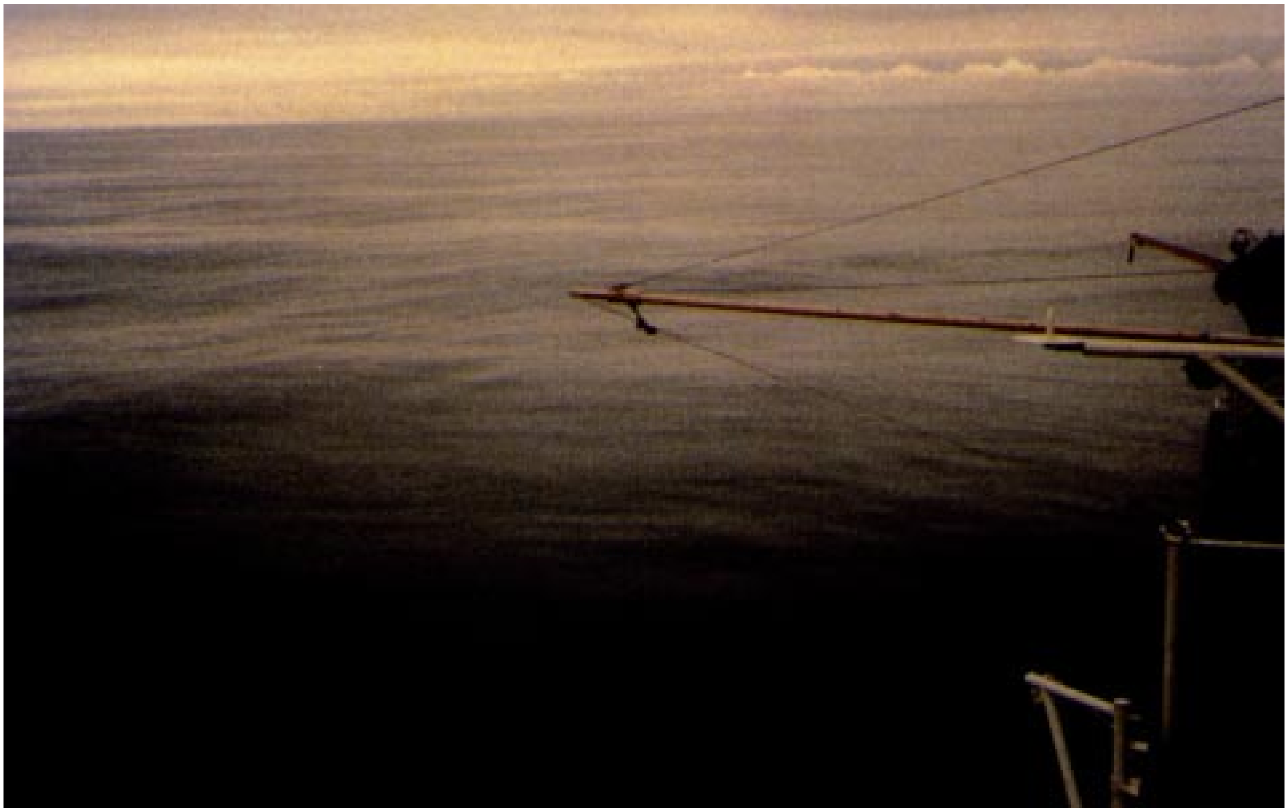
Radar and satellite observations are now almost universally used to forecast weather for both the short and long term. New techniques such as Doppler radar, and the integration of data from many different sites into complex computer algorithms provide a method of predicting storm tracks with a high degree of accuracy. Tornadoes, line squalls, individual thunderstorms, and entire storm systems can be continuously tracked and their paths predicted with unprecedented accuracy. At sea, the mariner has immediate access to this data through facsimile transmission of synoptic charts and actual satellite photographs, and through radio or communications satellite contact with weather routing services.

Automated weather stations and buoy systems provide regular transmissions of meteorological and oceanographic information by radio. They are generally used at isolated and relatively inaccessible locations from which weather and ocean data are of great importance. Depending on the type of system used, the elements usually measured include wind direction and speed, atmospheric pressure, air and sea surface temperature, spectral wave data, and a temperature profile from the sea surface to a predetermined depth.

Regardless of advances in the technology of observing and forecasting, the shipboard weather report remains the cornerstone upon which the accuracy of many forecasts is based. Each of the new observing methods is subject to limitations and occasional failures. The most reliable and complete source of weather data for offshore areas remains the shipboard observer.

3722. Recording Observations

Instructions for recording weather observations aboard vessels of the United States Navy are given in NAVMETOCCOMINST 3144.1 (series), Shipboard Weather Observations. Instructions for recording observations aboard merchant vessels are given in the National Weather Service Observing Handbook No. 1, Marine Surface Observations.



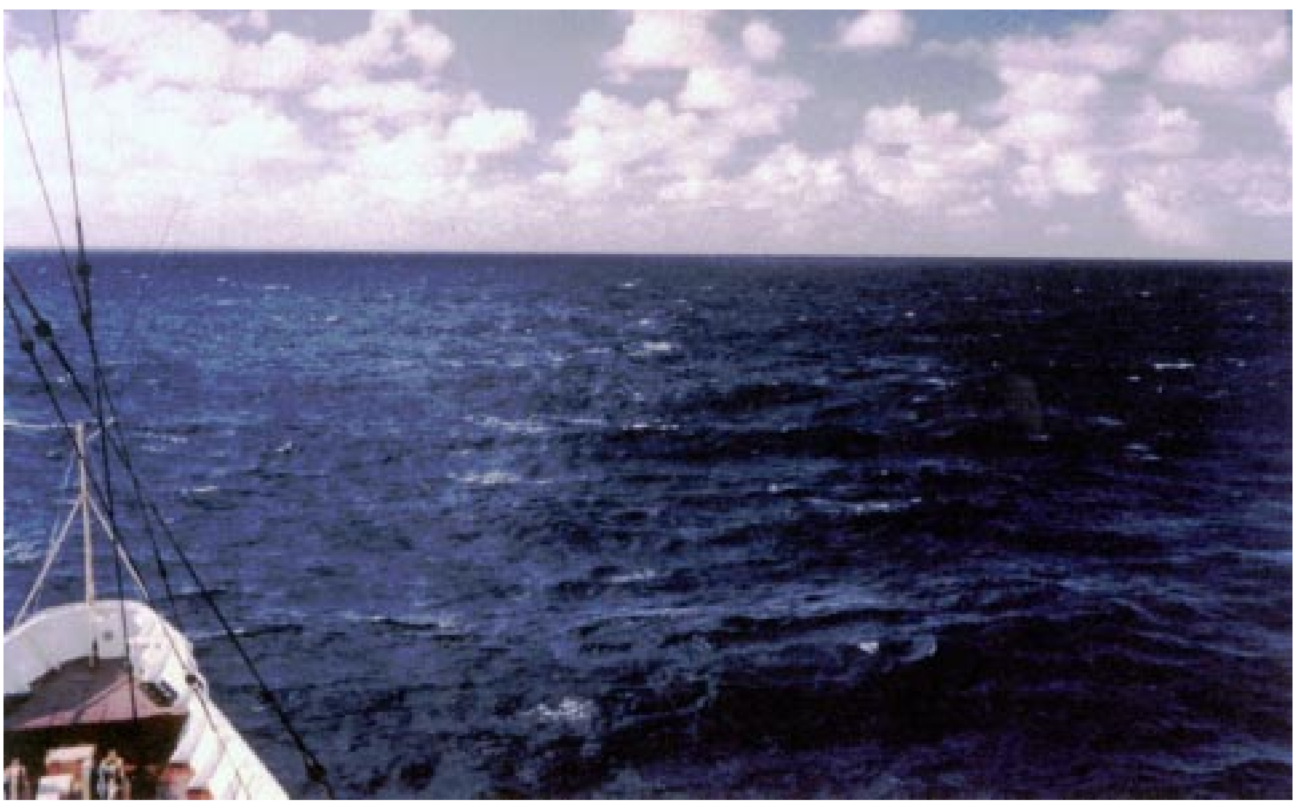
Force 0: Wind Speed less than 1 knot.
Sea: Sea like a mirror.

Force 1: Wind Speed 1-3 knots.
Sea: Wave height .1m (.25 ft); Ripples with appearance of scales, no foam crests.

Force 2: Wind Speed 4-6 knots.
Sea: Wave height .2-.3m (.5-1 ft); Small wavelets, crests of glassy appearance, not breaking.

Force 3: Wind Speed 7-10 knots.
Sea: Wave height .6-1m (2-3 ft); Large wavelets, crests begin to break, scattered whitecaps.

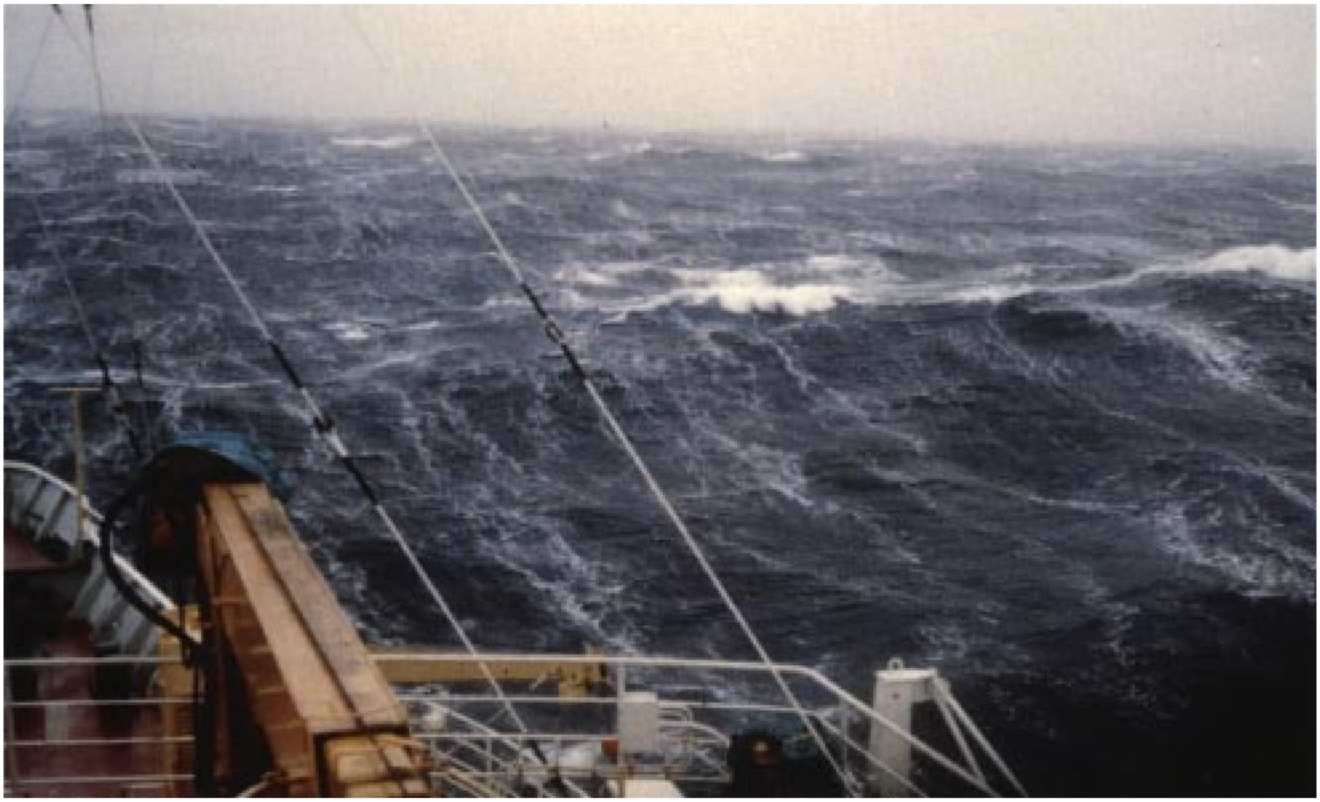
Force 4: Wind Speed 11-16 knots.
Sea: Wave height 1-1.5m (3.5-5 ft); Small waves becoming longer, numerous whitecaps.



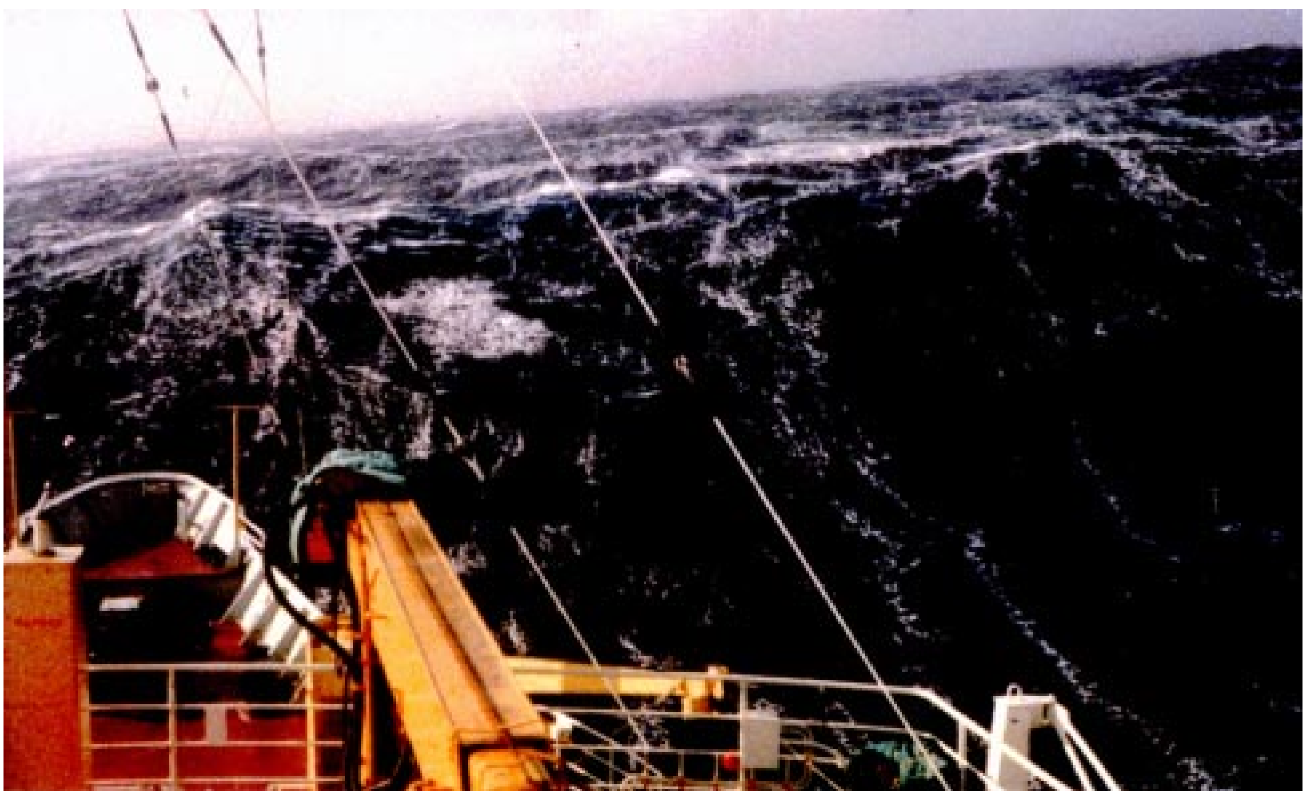
Force 5: Wind Speed 17-21 knots.
Sea: Wave height 2-2.5m (6-8 ft); Moderate waves, taking longer form, many whitecaps, some spray.

Force 6: Wind Speed 22-27 knots.
Sea: Wave height 3-4m (9.5-13 ft); Larger waves forming, whitecaps everywhere, more spray.

Force 7: Wind Speed 28-33 knots.
Sea: Wave height 4-5.5m (13.5-19 ft); sea heaps up, white foam from breaking waves begins to be blown in streaks along direction of wind.



Force 8: Wind Speed 34-40 knots.
Sea: Wave height 5.5-7.5m (18-25 ft); Moderately high waves of greater length, edges of crests begin to break into spindrift, foam is blown in well marked streaks.



Force 9: Wind Speed 41-47 knots.
Sea: Wave height 7-10m (23-32 ft); High waves, sea begins to roll, dense streaks of foam along wind direction, spray may reduce visibility.

Force 10: Wind Speed 48-55 knots (storm).
Sea: Wave height 9-12.5m (29-41 ft); Very high waves with overhanging crests, sea takes white appearance as foam is blown in very dense streaks, rolling is heavy and shocklike, visibility is reduced.

Force 11: Wind Speed 56-63 knots.
Sea: Wave height 11.5-16m (37-52 ft); Exceptionally high waves, sea covered with white foam patches, visibility still more reduced.

CHAPTER 38

WEATHER ROUTING

PRINCIPLES OF WEATHER ROUTING

3800. Introduction

Ship weather routing develops an optimum track for ocean voyages based on forecasts of weather, sea conditions, and a ship's individual characteristics for a particular transit. Within specified limits of weather and sea conditions, the term optimum is used to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any desired combination of these factors. The purpose of this chapter is to acquaint the mariner with the basic philosophy and procedures of ship weather routing as an aid to understanding the routing agency's recommendations.

The mariner's first resources for route planning in relation to weather are the Pilot Chart Atlases and the Sailing Directions (Planning Guides). These publications give climatic data, such as wave height frequencies and ice limits, for the major ocean basins of the world. They recommend specific routes based on probabilities, but not on specific conditions.

The ship routing agency, acting as an advisory service, attempts to avoid or reduce the effects of specific adverse weather and sea conditions by issuing initial route recommendations prior to sailing, recommendations for track changes while underway (diversions), and weather advisories to alert the commanding officer or master about approaching unfavorable weather and sea conditions which cannot be effectively avoided by a diversion. Adverse weather and sea conditions are defined as those conditions which will cause damage, significant speed reduction, or time loss.

The initial route recommendation is based on a survey of weather and sea forecasts between the point of departure and the destination. It takes into account the hull type, speed capability, cargo, and loading conditions. The ship's progress is continually monitored, and, if adverse weather and sea conditions are forecast along the ship's current track, a recommendation for a diversion or weather advisory is transmitted to the ship. By this process of initial route selection and continued monitoring of the ship's progress for possible changes in the forecast weather and sea conditions along a route, it is possible to maximize the ship's speed and safety.

In providing optimum sailing conditions, the advisory service also attempts to reduce transit time by avoiding the adverse conditions which may be encountered on a shorter route, or if the forecasts permit, diverting to a shorter track to take advantage of favorable weather and sea conditions. The greatest potential advantage for this ship weather routing exists when: (1) the passage is relatively long, about 1,500 miles or more; (2) the waters are navigationally unrestricted, so that there is a choice of routes; and (3) weather is a factor in determining the route to be followed.

Use of this advisory service in no way relieves the commanding officer or master of responsibility for prudent seamanship and safe navigation. There is no intent by the routing agency to inhibit the exercise of professional judgment and prerogatives of commanding officers and masters.

3801. Historical Perspective

The advent of extended range forecasting and the development of selective climatology, along with powerful computer modeling techniques, have made ship routing systems possible. The ability to effectively advise ships to take advantage of favorable weather was hampered previously by forecast limitations and the lack of an effective communications system.

Development work in the area of data accumulation and climatology has a long history. Benjamin Franklin, as deputy postmaster general of the British Colonies in North America, produced a chart of the Gulf Stream from information supplied by masters of New England whaling ships. This first mapping of the Gulf Stream helped improve the mail packet service between the British Colonies and England. In some passages the sailing time was reduced by as much as 14 days over routes previously sailed. In the mid-19th century, Matthew Fontaine Maury compiled large amounts of atmospheric and oceanographic data from ships' log books. For the first time, a climatology of ocean weather and currents of the world was available to the mariner. This information was used by Maury to develop seasonally recommended routes for sailing ships and early steam powered vessels in the latter half of the 19th century. In many cases, Maury's charts were proved correct by the savings in transit time. Average transit time on the New York to California via Cape Horn route was reduced from 183 days to 139 days with the use of his recommended seasonal routes.

In the 1950's the concept of ship weather routing was put into operation by several private meteorological groups and by the U.S. Navy. By applying the available surface and upper air forecasts to transoceanic shipping, it was possible to effectively avoid much heavy weather while generally

sailing shorter routes than previously.

Optimum Track Ship Routing (OTSR), the ship routing service of the U.S. Navy, utilizes short range and extended range forecasting techniques in route selection and surveillance procedures. The short range dynamic forecasts of 3 to 5 days are derived from meteorological equations. These forecasts are computed twice daily from a data base of northern hemisphere surface and upper air observations, and include surface pressure, upper air constant pressure heights, and the spectral wave values. A significant increase in data input, particularly from satellite information over ocean areas, can extend the time period for which these forecasts are useful.

For extended range forecasting, generally 3 to 14 days, a computer searches a library of historical northern hemisphere surface pressure and 500 millibar analyses for an analogous weather pattern. This is an attempt at selective climatology by matching the current weather pattern with past weather patterns and providing a logical sequence-of-events forecast for the 10 to 14 day period following the dynamic forecast. It is performed for both the Atlantic and Pacific Oceans using climatological data for the entire period of data stored in the computer. For longer ocean transits, monthly values of wind, seas, fog, and ocean currents are used to further extend the time range.

Aviation was first in applying the principle of minimum time tracks (MTT) to a changing wind field. But the problem of finding an MTT for a specific flight is much simpler than for a transoceanic ship passage because an aircraft's transit time is much shorter than a ship's. Thus, marine minimum time tracks require significantly longer range forecasts to develop an optimum route.

Automation has enabled ship routing agencies to develop realistic minimum time tracks. Computation of minimum time tracks makes use of:

1. A navigation system to compute route distance, time enroute, estimated times of arrival (ETA's), and to provide 6 hourly DR synoptic positions for the range of the dynamic forecasts for the ship's current track.
2. A surveillance system to survey wind, seas, fog, and ocean currents obtained from the dynamic and climatological fields.
3. An environmental constraint system imposed as part of the route selection and surveillance process. Constraints are the upper limits of wind and seas desired for the transit. They are determined by the ship's loading, speed capability, and vulnerability. The constraint system is an important part of the route selection process and acts as a warning system when the weather and sea forecast along the present track exceeds predetermined limits.
4. Ship speed characteristics used to approximate ship's speed of advance (SOA) while transiting the forecast sea states.

Ship weather routing services are being offered by many nations. These include Japan, United Kingdom, Russia, Netherlands, Germany, and the United States. Also, several private firms provide routing services to shipping industry clients.

There are two general types of commercial ship routing services. The first uses techniques similar to the Navy's OTSR system to forecast conditions and compute routing recommendations. The second assembles and processes weather and sea condition data and transmits this to ships at sea for on-board processing and generation of route recommendations. The former system allows for greater computer power to be applied to the routing task because powerful computers are available ashore. The latter system allows greater flexibility to the ship's master in changing parameters, selecting routes, and displaying data.

3802. Ship And Cargo Considerations

Ship and cargo characteristics have a significant influence on the application of ship weather routing. Ship size, speed capability, and type of cargo are important considerations in the route selection process prior to sailing and the surveillance procedure while underway. A ship's characteristics identify its vulnerability to adverse conditions and its ability to avoid them.

Generally, ships with higher speed capability and less cargo encumbrances will have shorter routes and be better able to maintain near normal SOA's than ships with lower speed capability or cargoes. Some routes are unique because of the type of ship or cargo. Avoiding one element of weather to reduce pounding or rolling may be of prime importance. For example, a 20 knot ship with a heavy deck cargo may be severely hampered in its ability to maintain a 20 knot SOA in any seas exceeding moderate head or beam seas because of the possibility of damage resulting from the deck load's characteristics. A similar ship with a stable cargo under the deck is not as vulnerable and may be able to maintain the 20 knot SOA in conditions which would drastically slow the deck-loaded vessel. In towing operations, a tug is more vulnerable to adverse weather and sea conditions, not only in consideration of the tow, but also because of its already limited speed capability. Its slow speed adds to the difficulty of avoiding adverse weather and sea conditions.

Ship performance curves (speed curves) are used to estimate the ship's SOA while transiting the forecast sea states. The curves indicate the effect of head, beam, and following seas of various significant wave heights on the ship's speed. Figure 3802 is a performance curve prepared for an 18 knot vessel.

With the speed curves it is possible to determine just how costly a diversion will be in terms of the required distance and time. A diversion may not be necessary where the duration of the adverse conditions is limited. In this case, it may be better to ride out the weather and seas knowing that

a diversion, even if able to maintain the normal SOA, will not overcome the increased distance and time required.

At other times, the diversion track is less costly because it avoids an area of adverse weather and sea conditions, while being able to maintain normal SOA even though the distance to destination is increased. Based on input data for environmental conditions and ship's behavior, route selection and surveillance techniques seek to achieve the optimum balance between time, distance, and acceptable environmental and seakeeping conditions. Although speed performance curves are an aid to the ship routing agency, the response by mariners to deteriorating weather and sea conditions is not uniform. Some reduce speed voluntarily or change heading sooner than others when unfavorable conditions are encountered. Certain waves with characteristics such that the ship's bow and stern are in successive crests and troughs present special problems for the mariner. Being nearly equal to the ship's length, such wavelengths may induce very dangerous stresses. The degree of hogging and sagging and the associated danger may be more apparent to the mariner than to the ship routing agency. Therefore, adjustment in course and speed for a more favorable ride may be initiated by the commanding officer or master when this situation is encountered.

3803. Environmental Factors

Environmental factors of importance to ship weather routing are those elements of the atmosphere and ocean that may produce a change in the status of a ship transit. In ship routing, consideration is given to wind, seas, fog, ice, and ocean currents. While all of the environmental factors are important for route selection and surveillance, optimum routing is normally considered attained if the effects of wind and seas can be optimized.

Wind: The effect of wind speed on ship performance is difficult to determine. In light winds (less than 20-knots), ships lose speed in headwinds and gain speed slightly in following winds. For higher wind speeds, ship speed is reduced in both head and following winds. This is due to the increased wave action, which even in following seas results in increased drag from steering corrections, and indicates the importance of sea conditions in determining ship performance. In dealing with wind, it is also necessary to know the ship's sail area. High winds will have a greater adverse effect on a large, fully loaded container ship or car carrier than a fully loaded tanker of similar length. This effect is most noticeable when docking, but the effect of beam winds over several days at sea can also be considerable.

Wave Height: Wave height is the major factor affecting ship performance. Wave action is responsible for ship motions which reduce propeller thrust and cause increased drag from steering corrections. The relationship of ship speed to wave direction and height is similar to that of wind. Head seas reduce ship speed, while following seas increase ship speed slightly to a certain point, beyond which they retard it. In heavy seas, exact performance may be difficult to predict because of the adjustments to course and speed for shiphandling and comfort. Although the effect of sea and swell is much greater than wind, it is difficult to separate the two in ship routing.

In an effort to provide a more detailed description of the actual and forecast sea state, the U.S. Navy Fleet Numerical Meteorology and Oceanography Center,

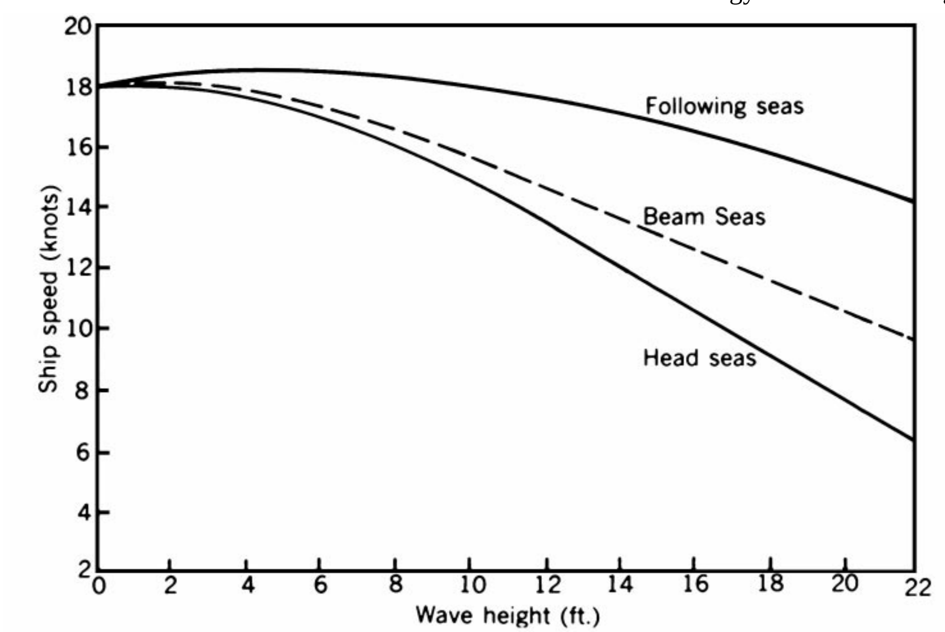


Figure 3802. Performance curves for head, beam, and following seas.

Monterey, California, produces the Global Spectral Ocean Wave Model (GSOWM) for use by the U.S. Navy's Optimum Track Ship Routing (OTSR) service. This model provides energy values from 12 different directions (30° sectors) and 15 frequency bands for wave periods from 6 to 26 seconds with the total wave energy propagated throughout the grid system as a function of direction and frequency. It is based on the analyzed and forecast planetary boundary layer model wind fields, and is produced for both the Northern and Southern Hemispheres out to 72 hours. For OTSR purposes, primary and secondary waves are derived from the spectral wave program, where the primary wave train has the principal energy (direction and frequency), and the secondary has to be 20 percent of the primary.

Fog: Fog, while not directly affecting ship performance, should be avoided as much as feasible, in order to maintain normal speed in safe conditions. Extensive areas of fog during summertime can be avoided by selecting a lower latitude route than one based solely upon wind and seas. Although the route may be longer, transit time may be less due to not having to reduce speed in reduced visibility. In addition, crew fatigue due to increased watchkeeping vigilance can be reduced.

North Wall Effect: During the Northern Hemisphere fall and winter, the waters to the north of the Gulf Stream in the North Atlantic are at their coldest, while the Gulf Stream itself remains at a constant relatively warm temperature. After passage of a strong cold front or behind a developing coastal low pressure system, Arctic air is sometimes drawn off the Mid-Atlantic coast of the United States and out over the warm waters of the Gulf Stream by northerly winds. This cold air is warmed as it passes over the Gulf Stream, resulting in rapid and intense deepening of the low pressure system and higher than normal surface winds. Higher waves and confused seas result from these winds. When these winds oppose the northeast set of the current, the result is increased wave heights and a shortening of the wave period. If the opposing current is sufficiently strong, the waves will break. These phenomena are collectively called the "North Wall Effect," referring to the region of most dramatic temperature change between the cold water to the north and the warm Gulf Stream water to the south. The most dangerous aspect of this phenomenon is that the strong winds and extremely high, steep waves occur in a limited area and may develop without warning. Thus, a ship that is laboring in near-gale force northerly winds and rough seas, proceeding on a northerly course, can suddenly encounter storm force winds and dangerously high breaking seas. Numerous ships have foundered off the North American coast in the approximate position of the Gulf Stream's North Wall. A similar phenomenon occurs in the North Pacific near the Kuroshio Current and off the Southeast African coast near the Agulhas Current.

Ocean Currents: Ocean currents do not present a significant routing problem, but they can be a determining factor in route selection and diversion. This is especially true when the points of departure and destination are at relatively low latitudes. The important considerations to be evaluated are the difference in distance between a great-circle route and a route selected for optimum current, with the expected increase in SOA from the following current, and the decreased probability of a diversion for weather and seas at the lower latitude. For example, it has proven beneficial to remain equatorward of approximately 22°N for westbound passages between the Canal Zone and southwest Pacific ports. For eastbound passages, if the maximum latitude on a great-circle track from the southwest Pacific to the Canal Zone is below 24°N, a route passing near the axis of the Equatorial Countercurrent is practical because the increased distance is offset by favorable current. Direction and speed of ocean currents are more predictable than wind and seas, but some variability can be expected. Major ocean currents can be disrupted for several days by very intense weather systems such as hurricanes and by global phenomena such as El Nino.

Ice: The problem of ice is twofold: floating ice (icebergs) and deck ice. If possible, areas of icebergs or pack ice should be avoided because of the difficulty of detection and the potential for collision. Deck ice may be more difficult to contend with from a ship routing point of view because it is caused by freezing weather associated with a large weather system. While mostly a nuisance factor on large ships, it causes significant problems with the stability of small ships.

Latitude: Generally, the higher the latitude of a route, even in the summer, the greater are the problems with the environment. Certain operations should benefit from seasonal planning as well as optimum routing. For example, towing operations north of about 40° latitude should be avoided in non-summer months if possible.

3804. Synoptic Weather Considerations

A ship routing agency should direct its forecasting skills to avoiding or limiting the effect of weather and seas associated with extratropical low pressure systems in the mid and higher latitudes and the tropical systems in low latitude. Seasonal or monsoon weather is also a factor in route selection and diversion in certain areas.

Despite the amount of attention and publicity given to tropical cyclones, mid-latitude low pressure systems generally present more difficult problems to a ship routing agency. This is primarily due to the fact that major ship traffic is sailing in the latitudes of the migrating low pressure systems, and the amount of potential exposure to intense weather systems, especially in winter, is much greater.

Low pressure systems weaker than gale intensity (winds less than 34 knots) are not a severe problem for most ships. However, a relatively weak system may generate prolonged periods of rough seas which may hamper normal

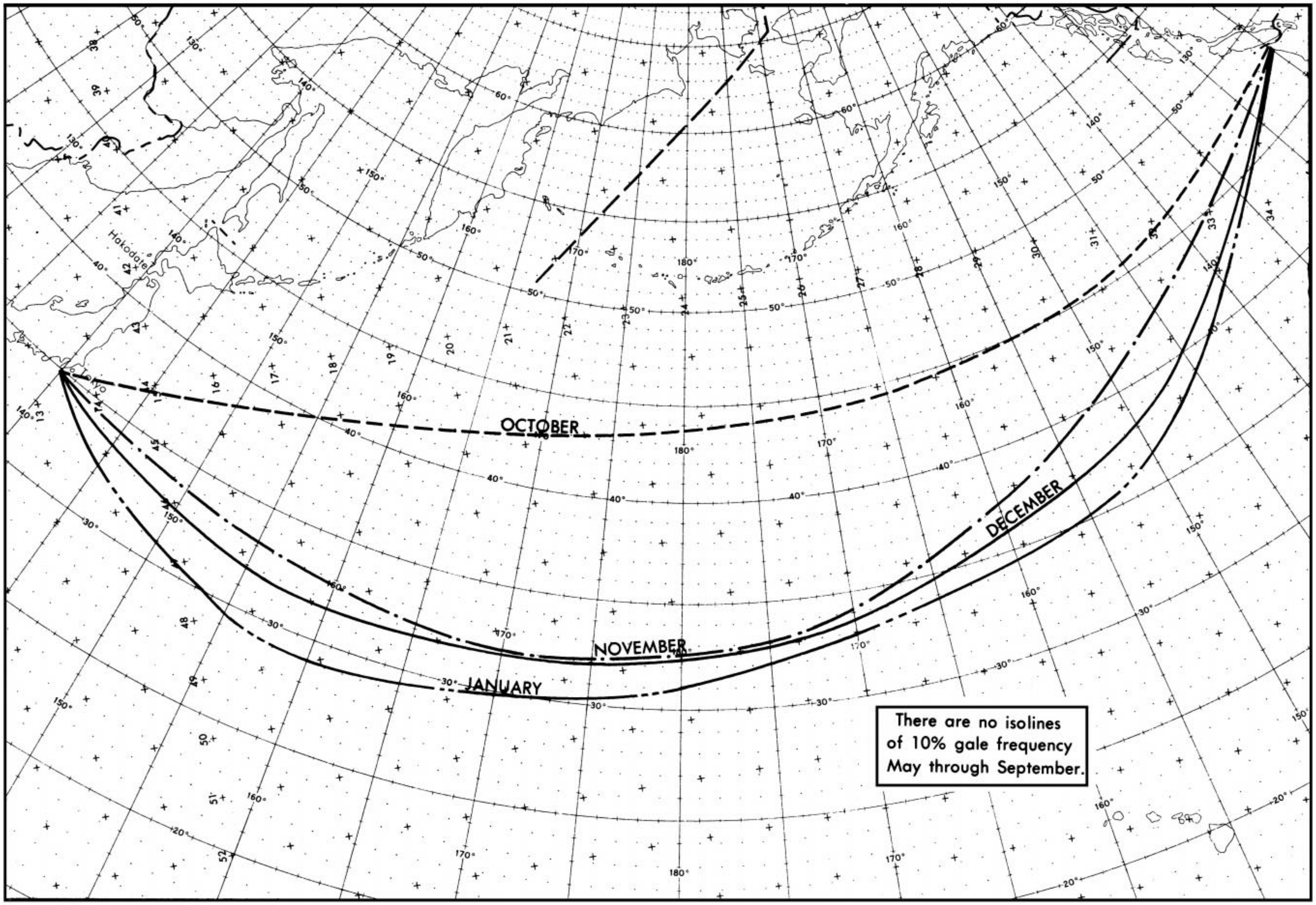


Figure 3804a. Generalized 10% frequency isolines of gale force winds for October through January.

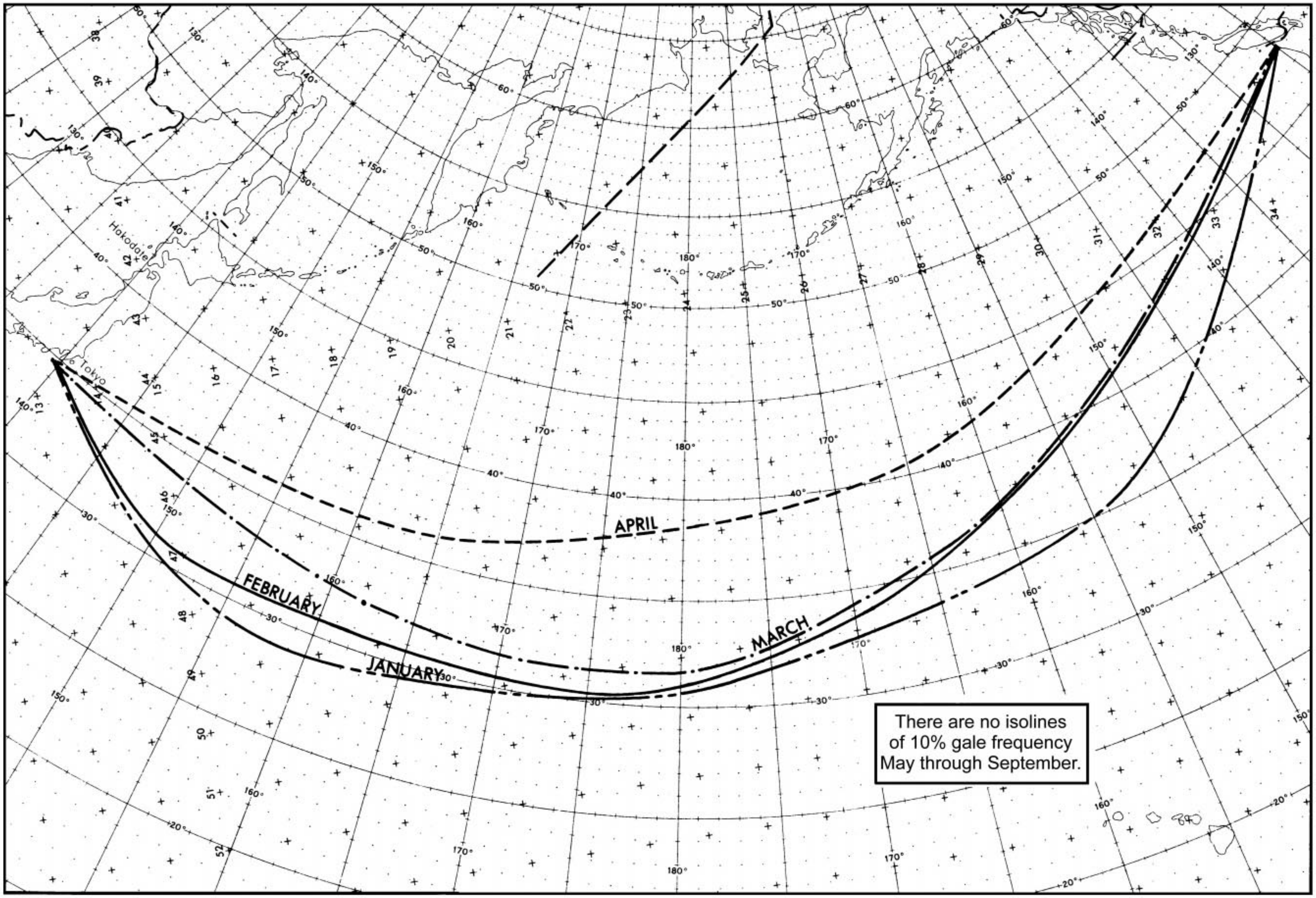


Figure 3804b. Generalized 10% frequency isolines of gale force winds for January through April..

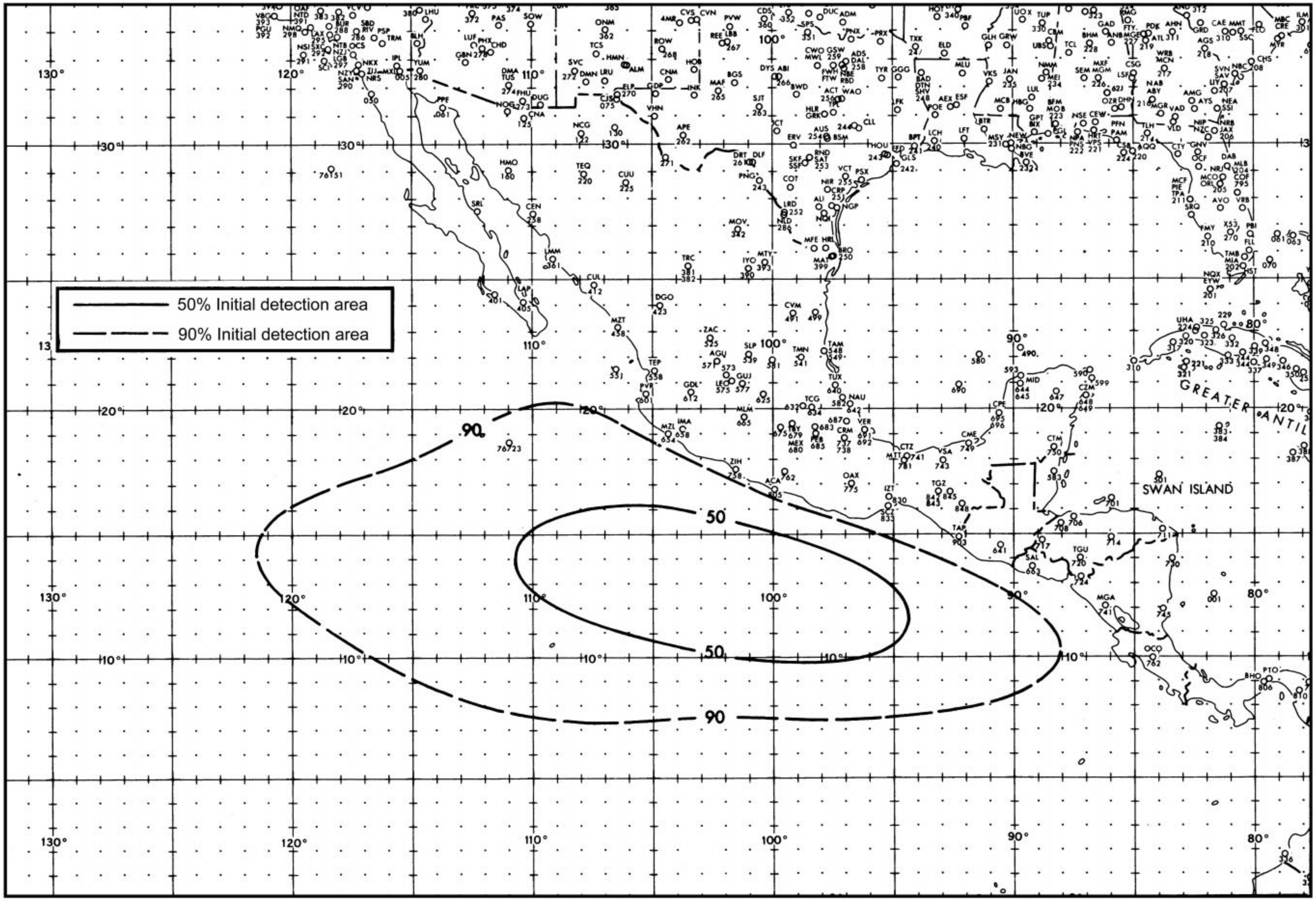


Figure 3804c. Area of initial detection of high percentage of tropical cyclones which later developed to tropical storm or typhoon intensity, 1957-1974.

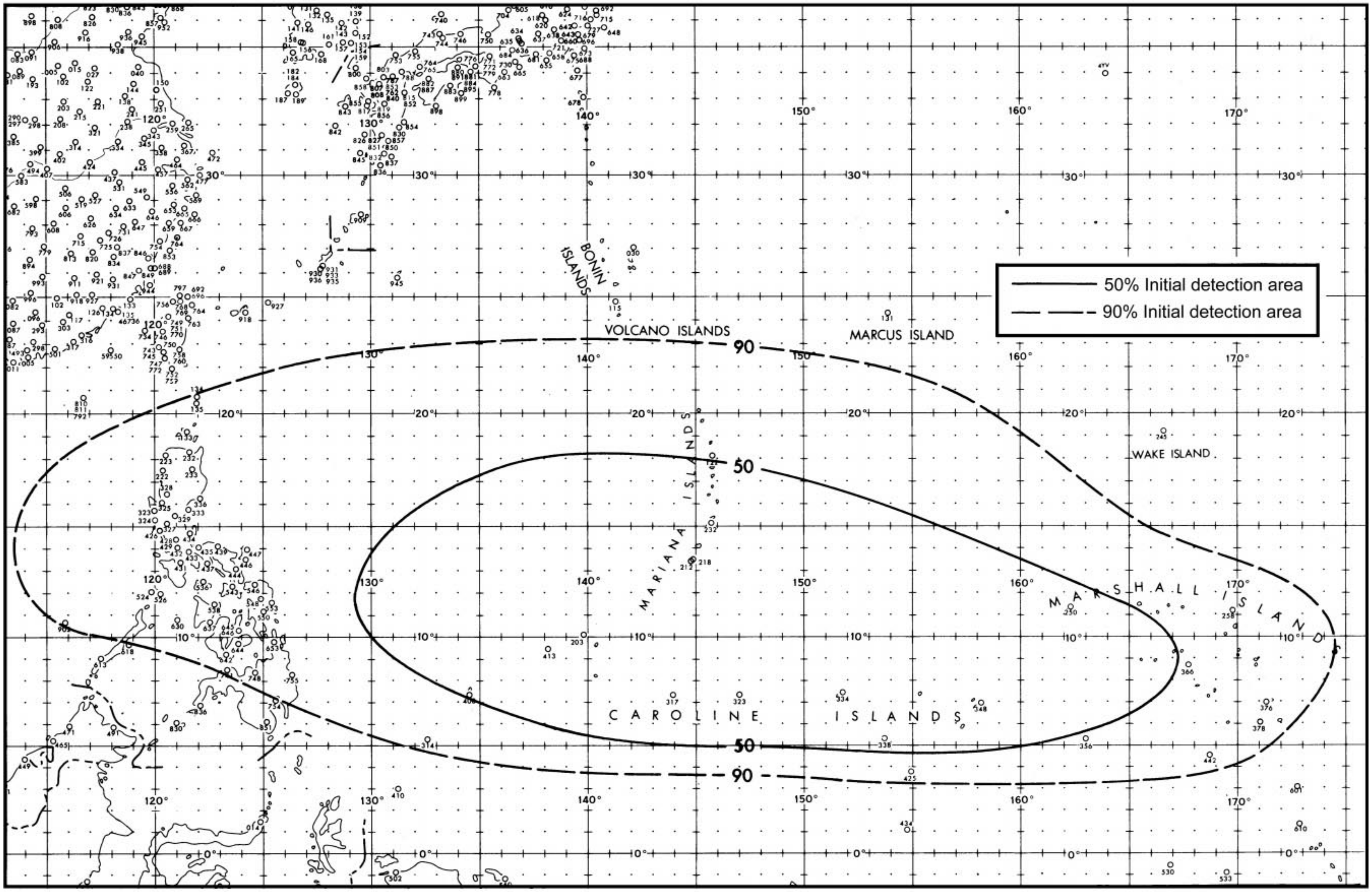


Figure 3804d.. Area of initial detection of high percentage of tropical cyclones which later developed to tropical storm or hurricaine intensity, 1946-1973

work aboard ship. Ship weather routing can frequently limit rough conditions to short periods of time and provide more favorable conditions for most of the transit. Relatively small ships, tugs with tows, low powered ships, and ships with sensitive cargoes can be significantly affected by weather systems weaker than gale intensity. Using a routing agency can be beneficial.

Gales (winds 34 to 47 knots) and storms (winds greater than 48 knots) in the open sea can generate very rough or high seas, particularly when an adverse current such as the Gulf Stream is involved. This can force a reduction in speed in order to gain a more comfortable and safe ride. Because of the extensive geographic area covered by a well developed low pressure system, once ship's speed is reduced the ability to improve the ship's situation is severely hampered. Thus, exposure to potential damage and danger is greatly increased. A recommendation for a diversion by a routing agency well in advance of the intense weather and associated seas will limit the duration of exposure of the ship. If effective, ship speed will not be reduced and satisfactory progress will be maintained even though the remaining distance to destination is increased. Overall transit time is usually shorter than if no track change had been made and the ship had remained in heavy weather. In some cases diversions are made to avoid adverse weather conditions and shorten the track at the same time. Significant savings in time and costs can result.

In very intense low pressure systems, with high winds and long duration over a long fetch, seas will be generated and propagated as swell over considerable distances. Even on a diversion, it is difficult to effectively avoid all unfavorable conditions. Generally, original routes for transoceanic passages, issued by the U.S. Navy's ship routing service, are equatorward of the 10% frequency isoline for gale force winds for the month of transit, as interpreted from the U.S. Navy's Marine Climatic Atlas of the World. These are shown in Figure 3804a and Figure 3804b for the Pacific. To avoid the area of significant gale activity in the Atlantic from October to April, the latitude of transit is generally in the lower thirties.

The areas, seasons, and the probability of development of tropical cyclones are fairly well defined in climatological publications. In long range planning, considerable benefit can be gained by limiting the exposure to the potential hazards of tropical systems.

In the North Pacific, avoid areas with the greatest probability of tropical cyclone formation. Avoiding existing tropical cyclones with a history of 24 hours or more of 6-hourly warnings is in most cases relatively straightforward. However, when transiting the tropical cyclone generating area, the ship under routing may provide the first report of environmental conditions indicating that a new disturbance is developing. In the eastern North Pacific the generating area for a high percentage of tropical cyclones is relatively compact (Figure 3804c). Remain south of a line from lat. 9°N, long. 90°W to lat. 14°N, long. 115°W. In the western North Pacific it is advisable to hold north of 22°N when no tropical systems are known to exist. See Figure 3804d.

In the Atlantic , sail near the axis of the Bermuda high or northward to avoid the area of formation of tropical cyclones. Of course, avoiding an existing tropical cyclone takes precedence over avoiding a general area of potential development.

It has proven equally beneficial to employ similar considerations for routing in the monsoon areas of the Indian Ocean and the South China Sea. This is accomplished by providing routes and diversions that generally avoid the areas of high frequency of gale force winds and associated heavy seas, as much as feasible. Ships can then remain in satisfactory conditions with limited increases in route distance.

Depending upon the points of departure and destination, there are many combinations of routes that can be used when transiting the northern Indian Ocean (Arabian Sea, Bay of Bengal) and the South China Sea. For example, in the Arabian Sea during the summer monsoon, routes to and from the Red Sea, the western Pacific, and the eastern Indian Ocean should hold equatorward. Ships proceeding to the Persian Gulf during this period are held farther south and west to put the heaviest seas on the quarter or stern when transiting the Arabian Sea. Eastbound ships departing the Persian Gulf may proceed generally east southeast toward the Indian subcontinent, then south, to pass north and east of the highest southwesterly seas in the Arabian Sea. Westbound ships out of the Persian Gulf for the Cape of Good Hope appear to have little choice in routes unless considerable distance is added to the transit by passing east of the highest seas. In the winter monsoon, routes to or from the Red Sea for the western Pacific and the Indian Ocean are held farther north in the Arabian Sea to avoid the highest seas. Ships proceeding to the Persian Gulf from the western Pacific and eastern Indian Ocean may hold more eastward when proceeding north in the Arabian Sea. Ships departing the Persian Gulf area will have considerably less difficulty than during the summer monsoon. Similar considerations can be given when routing ships proceeding to and from the Bay of Bengal.

In the South China Sea, transits via the Palawan Passage are recommended when strong, opposing wind and seas are forecast. This is especially true during the winter monsoon. During periods when the major monsoon flow is slack, ships can use the shortest track as conditions permit.

3805. Special Weather And Environmental Considerations

In addition to the synoptic weather considerations in ship weather routing, there are special environmental problems that can be avoided by following recommendations and advisories of ship routing agencies. These problems generally cover a smaller geographic area and are seasonal in nature, but are still important to ship routing.

In the North Atlantic, because of heavy shipping traffic, frequent poor visibility in rain or fog, and restricted navigation, particularly east of Dover Strait, some mariners

prefer to transit to or from the North Sea via Pentland Firth, passing north of the British Isles rather than via the English Channel.

Weather routed ships generally avoid the area of dense fog with low visibility in the vicinity of the Grand Banks off Newfoundland and the area east of Japan north of 35°N. Fishing vessels in these two areas provide an added hazard to safe navigation. This condition exists primarily from June through September. Arctic supply ships en route from the U.S. east coast to the Davis Strait-Baffin Bay area in the summer frequently transit via Cabot Strait and the Strait of Belle Isle, where navigation aids are available and icebergs are generally grounded.

Icebergs are a definite hazard in the North Atlantic from late February through June, and occasionally later. The hazard of floating ice is frequently combined with restricted visibility in fog. International Ice Patrol reports and warnings are incorporated into the planning of routes to safely avoid dangerous iceberg areas. It is usually necessary to hold south of at least 45°N until well southeast of Newfoundland. The U.S. Navy ship routing office at the Naval Atlantic Meteorology and Oceanography Center in Norfolk maintains a safety margin of at least 100 miles from icebergs reported by the International Ice Patrol. Also, in a severe winter, the Denmark Strait may be closed by ice.

In the northern hemisphere winter, a strong high pressure system moving southeast out of the Rocky Mountains brings cold air down across Central America and the western Gulf of Mexico producing gale force winds in the Gulf of Tehuantepec. This fall wind is similar to the pampero, mistral, and bora of other areas of the world. An adjustment to ship's track can successfully avoid the highest seas associated with the "Tehuantepecer." For transits between the Canal Zone and northwest Pacific ports, little additional distance is required to avoid this area (in winter) by remaining south of at least 12°N when crossing 97°W. While avoiding the highest seas, some unfavorable swell conditions may be encountered south of this line. Ships transiting between the Panama Canal and North American west coast ports can stay close along the coast of the Gulf of Tehuantepec to avoid heavy seas during gale conditions, but may still encounter high offshore winds.

In the summer, the semi-permanent high pressure systems over the world's oceans produce strong equatorward flow along the west coasts of continents. This feature is most pronounced off the coast of California and Portugal in the Northern Hemisphere and along Chile, western Australia, and southwest Africa in the Southern Hemisphere. Very rough seas are generated and are considered a definite factor in route selection or diversion when transiting these areas.

3806. Types Of Recommendations And Advisories

An **initial route recommendation** is issued to a ship or routing authority normally 48 to 72 hours prior to sailing, and the process of surveillance begins. Surveillance is a continuous process, maintained until the ship arrives at its destination. Initial route recommendations are a composite representation of experience, climatology, weather and sea state forecasts, operational concerns, and the ship's seagoing characteristics. A planning route provides a best estimate of a realistic route for a specific transit period. Such routes are provided when estimated dates of departure (EDD's) are given to the routing agency well in advance of departure, usually a week to several months. Long range planning routes are based more on seasonal and climatological expectations than the current weather situation. While planning routes are an attempt to make extended range (more than a week) or long range (more than a month) forecasts, these recommendations are likely to be revised near the time of departure to reflect the current weather pattern. An initial route recommendation is more closely related to the current weather patterns by using the latest dynamic forecasts than are the planning route recommendations. These, too, are subject to revision prior to sailing, if weather and sea conditions warrant.

Adjustment of departure time is a recommendation for delay in departure, or early departure if feasible, and is intended to avoid or significantly reduce the adverse weather and seas forecast on the first portion of the route, if sailing on the original EDD. The initial route is not revised, only the timing of the ship's transit through an area with currently unfavorable weather conditions. Adjusting the departure time is an effective method of avoiding a potentially hazardous situation where there is no optimum route for sailing at the originally scheduled time.

A **diversion** is an underway adjustment in track and is intended to avoid or limit the effect of adverse weather conditions forecast to be encountered along the ship's current track. Ship's speed is expected to be reduced by the encounter with the heavy weather. In most cases the distance to destination is increased in attempting to avoid the adverse weather, but this is partially overcome by being able to maintain near normal SOA. Diversions are also recommended where satisfactory weather and sea conditions are forecast on a shorter track.

Adjustment of SOA is a recommendation for slowing or increasing the ship's speed as much as practicable, in an attempt to avoid an adverse weather situation by adjusting the timing of the encounter. This is also an effective means of maintaining maximum ship operating efficiency, while not diverting from the present ship's track. By adjusting the SOA, a major weather system can sometimes be avoided with no increase in distance. The development of fast ships (SOA greater than 30 knots) gives the ship routing agency the potential to "make the ship's weather" by adjusting the ship's speed and track for encounter with favorable weather conditions.

Evasion is a recommendation to the commanding officer or master to take independent action to avoid, as much as possible, a potentially dangerous weather system. The ship routing meteorologist may recommend a general direction for safe evasion but does not specify an exact track. The recommendation for evasion is an indication that the weather

and sea conditions have deteriorated to a point where shiphandling and safety are the primary considerations and progress toward destination has been temporarily suspended, or is at least of secondary consideration.

A **weather advisory** is a transmission sent to the ship advising the commanding officer or master of expected adverse conditions, their duration, and geographic extent. It is initiated by the ship routing agency as a service and an aid to the ship. The best example of a situation for which a forecast is helpful is when the ship is currently in good weather but adverse weather is expected within 24 hours for which a diversion has not been recommended, or a diversion where adverse weather conditions are still expected. This type of advisory may include a synoptic weather discussion, and a wind, seas, or fog forecast.

The ability of the routing agency to achieve optimum conditions for the ship is aided by the commanding officer or master adjusting course and speed where necessary for an efficient and safe ride. At times, the local sea conditions may dictate that the commanding officer or master take independent action.

3807. Southern Hemisphere Routing

Available data on which to base analyses and forecasts is generally very limited in the Southern Hemisphere. Weather and other environmental information obtained from satellites offers the possibility of improvement in southern hemisphere forecast products.

Passages south of the Cape of Good Hope and Cape Horn should be timed to avoid heavy weather as much as possible, since intense and frequent low pressure systems are common in these areas. In particular, near the southeast coasts of Africa and South America, intense low pressure systems form in the lee of relatively high terrain near the coasts of both continents. Winter transits south of Cape Horn are difficult, since the time required for transit is longer than the typical interval between storms. Remaining equatorward of about 35°S as much as practicable will limit exposure to adverse conditions. If the frequency of lows passing these areas is once every three or four days, the probability of encountering heavy weather is high.

Tropical cyclones in the Southern Hemisphere present a significant problem because of the sparse surface and upper air observations from which forecasts can be made. Satellites provide the most reliable means by which to obtain accurate positions of tropical systems, and also give the first indication of tropical cyclone formation.

In the Southern Hemisphere, OTSR and other ship weather routing services are available, but are limited in application because of sparse data reports, from which reliable short and extended range forecasts can be produced. Strong climatological consideration is usually given to any proposed southern hemisphere transit. OTSR procedures for the Northern Hemisphere can be instituted in the Southern Hemisphere whenever justified by basic data input and available forecast models.

3808. Communications

A vital part of a ship routing service is communication between the ship and the routing agency. Reports from the ship show the progress and ability to proceed in existing conditions. Weather reports from the ship enrich the basic data on which analyses are based and forecasts derived, assisting both the reporting ship and others in the vicinity.

Despite all efforts to achieve the best forecasts possible, the quality of forecasts does not always warrant maintaining the route selected. In the U.S. Navy's ship routing program, experience shows that one-third of the ships using OTSR receive some operational or weather-dependent change while underway.

The routing agency needs reports of the ship's position and the ability to transmit recommendations for track change or weather advisories to the ship. The ship needs both send and receive capability for the required information. Information on seakeeping changes initiated by the ship is desirable in a coordinated effort to provide optimum transit conditions. New satellite communications services are making possible the transmission of larger amounts of data than possible through traditional radio messages, a development which supports systems using on-board analysis to generate routes.

3809. Benefits

The benefits of ship weather routing services are primarily in cost reduction and safety. The savings in operating costs are derived from reductions in transit time, heavy weather encounters, fuel consumption, cargo and hull damage, and more efficient scheduling of dockside activities. The savings are further increased by fewer emergency repairs, more efficient use of personnel, improved topside working conditions, lower insurance rates as preferred risks under weather routing, and ultimately, extended ship operating life.

An effective routing service maximizes safety by greatly reducing the probability of severe or catastrophic damage to the ship, and injury of crew members. The efficiency and health of the crew is also enhanced by avoiding heavy weather. This is especially important on modern, automated ships with reduced crews.

3810. Conclusion

The success of ship weather routing is dependent upon the validity of the forecasts and the routing agency's ability to make appropriate route recommendations and diversions. Anticipated improvements in a routing agency's recommendations will come from advancements in meteorology, technology, and the application of ocean wave forecast models.

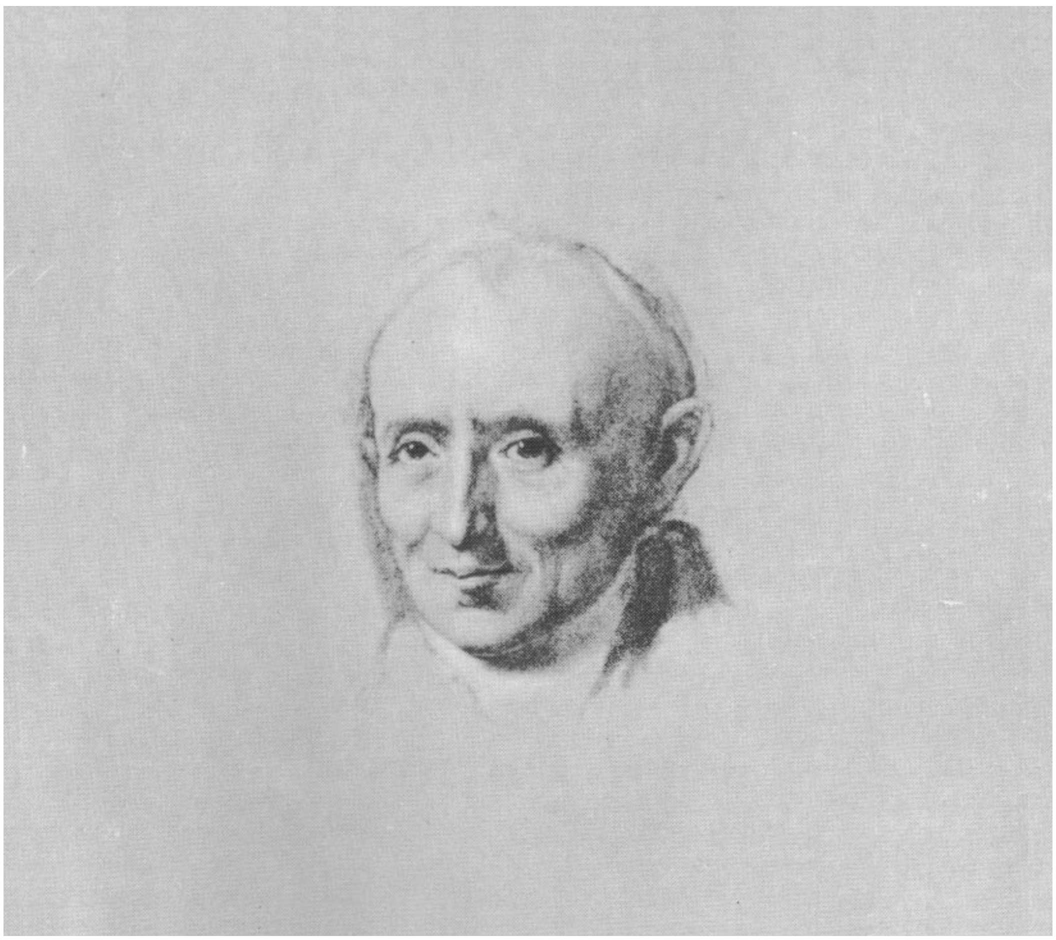
Advancements in mathematical meteorology, coupled with the continued application of computers, will extend the time range and accuracy of the dynamic and statistical forecasts.

Technological advancements in the areas of satellite and automated communications and onboard ship response systems will increase the amount and type of information to and from the ship with fewer delays. Ship response and performance data included with the ship's weather report will provide the routing agency with real-time information with which to ascertain the actual state of the ship. Being able to predict a ship's response in most weather and sea conditions will result in improved routing procedures.

Shipboard and anchored wave measuring devices contribute to the development of ocean wave analysis and forecast models. Shipboard seakeeping instrumentation, with input of measured wave conditions and predetermined ship response data for the particular hull, enables a master or commanding officer to adjust course and speed for actual conditions.

Modern ship designs, exotic cargoes, and sophisticated transport methods require individual attention to each ship's areas of vulnerability. Any improvement in the description of sea conditions by ocean wave models will improve the output from ship routing and seakeeping systems.

Advanced planning of a proposed transit, combined with the study of expected weather conditions, both before and during the voyage, as is done by ship routing agencies, and careful on board attention to seakeeping (with instrumentation if available) provide the greatest opportunity to achieve the goal of optimum environmental conditions for ocean transit.



Last painting by Gilbert Stuart (1828). Considered by the family of Bowditch to be the best of various paintings made, although it was unfinished when the artist died.

NATHANIEL BOWDITCH
(1773-1838)

Nathaniel Bowditch was born on March 26, 1773, in Salem, Mass., fourth of the seven children of shipmaster Habakkuk Bowditch and his wife, Mary.

Since the migration of William Bowditch from England to the Colonies in the 17th century, the family had resided at Salem. Most of its sons, like those of other families in this New England seaport, had gone to sea, and many of them became shipmasters. Nathaniel Bowditch himself sailed as master on his last voyage, and two of his brothers met untimely deaths while pursuing careers at sea.

It is reported that Nathaniel Bowditch's father lost two ships at sea, and by late Revolutionary days he returned to the trade of cooper, which he had learned in his youth. This provided insufficient income to properly supply the needs of his growing family, and hunger and cold were often experienced. For many years the nearly destitute family received an annual grant of 15 to 20 dollars from the Salem Marine Society. By the time Nathaniel had reached the age of 10, the family's poverty necessitated his leaving school and joining his father in the cooper's trade.

Nathaniel was unsuccessful as a cooper, and when he was about 12 years of age, he entered the first of two ship-chandlery firms by which he was employed. It was during the nearly 10 years he was so employed that his great mind first attracted public attention. From the time he began school Bowditch had an all-consuming interest in learning, particularly mathematics. By his middle teens he was recognized in Salem as an authority on that subject. Salem being primarily a shipping town, most of the inhabitants sooner or later found their way to the ship chandler, and news of the brilliant young clerk spread until eventually it came to the attention of the learned men of his day. Impressed by his desire to educate himself, they supplied him with books that he might learn of the discoveries of other men. Since many of the best books were written by Europeans, Bowditch first taught himself their languages. French, Spanish, Latin, Greek, and German were among the two dozen or more languages and dialects he studied during his life. At the age of 16 he began the study of Newton's *Principia*, translating parts of it from the Latin. He even found an error in that classic, and though lacking the confidence to announce it at the time, he later published his findings and had them accepted.

During the Revolutionary War a privateer out of Beverly, a neighboring town to Salem, had taken as one of its prizes an English vessel which was carrying the philosophical library of a famed Irish scholar, Dr. Richard Kirwan. The books were brought to the Colonies and there bought by a group of educated Salem men who used them to found the Philosophical Library Company, reputed to have been the best library north of Philadelphia at the time. In 1791, when Bowditch was 18, two Harvard-educated ministers, Rev. John Prince and Rev. William Bentley, persuaded the Company to allow Bowditch the use of its library. Encouraged by these two men and a third-Nathan Read, an apothecary and also a Harvard man-Bowditch studied the works of the great men who had preceded him, especially the mathematicians and the astronomers. By the time he became of age, this knowledge, acquired before and after his long working hours and in his spare time, had made young Bowditch the outstanding mathematician in the Commonwealth, and perhaps in the country.

In the seafaring town of Salem, Bowditch was drawn to navigation early, learning the subject at the age of 13 from an old British sailor. A year later he began studying surveying, and in 1794 he assisted in a survey of the town. At 15 he devised an almanac reputed to have been of great accuracy. His other youthful accomplishments included the construction of a crude barometer and a sundial.

When Bowditch went to sea at the age of 21, it was as captain's writer and nominal second mate, the officer's berth being offered him because of his reputation as a scholar. Under Captain Henry Prince, the ship *Henry* sailed from Salem in the winter of 1795 on what was to be a year-long voyage to the Ile de Bourbon (now called Reunion) in the Indian Ocean.

Bowditch began his seagoing career when accurate time was not available to the average naval or merchant ship. A reliable marine chronometer had been invented some 60 years before, but the prohibitive cost, plus the long voyages without opportunity to check the error of the timepiece, made the large investment an impractical one. A system of determining longitude by "lunar distance," a method which did not require an accurate timepiece, was known, but this product of the minds of mathematicians and astronomers was so involved as to be beyond the capabilities of the uneducated seamen of that day. Consequently, ships navigated by a combination of dead reckoning and parallel sailing (a system of sailing north or south to the latitude of the destination and then east or west to the destination). The navigational routine of the time was "lead, log, and lookout."

To Bowditch, the mathematical genius, computation of lunar distances was no mystery, of course, but he recognized the need for an easier method of working them in order to navigate ships more safely and efficiently. Through analysis and observation, he derived a new and simplified formula during his first trip.

John Hamilton Moore's *The Practical Navigator* was the leading navigational text when Bowditch first went to sea, and had been for many years. Early in his first voyage, however, the captain's writer-second mate began turning

up errors in Moore's book, and before long he found it necessary to recompute some of the tables he most often used in working his sights. Bowditch recorded the errors he found, and by the end of his second voyage, made in the higher capacity of supercargo, the news of his findings in *The New Practical Navigator* had reached Edmund Blunt, a printer at Newburyport, Mass. At Blunt's request, Bowditch agreed to participate with other learned men in the preparation of an American edition of the thirteenth (1798) edition of Moore's work. The first American edition was published at Newburyport by Blunt in 1799. This edition corrected many of the errors that Moore had failed to correct. Although most of the errors were of little significance to practical navigation as they were errors in the fifth and sixth places of logarithm tables, some errors were significant.

The most significant error was listing the year 1800 as a leap year in the table of the sun's declination. The consequence was that Moore gave the declination for MARCH 1, 1800, as 7°11'. Since the actual value was 7° 33', the calculation of a meridian altitude would be in error by 22 minutes of latitude.

Bowditch's principal contribution to the first American edition was his chapter "The Method of finding the Longitude at Sea," which was his new method for computing the lunar distance. Following publication of the first American edition, Blunt obtained Bowditch's services in checking the American and English editions for further errors. Blunt then published a second American edition of Moore's thirteenth edition in 1800. When preparing a third American edition for the press, Blunt decided that Bowditch had revised Moore's work to such an extent that Bowditch should be named as author. The title was changed to *The New American Practical Navigator* and the book was published in 1802 as a first edition. Bowditch vowed while writing this edition to "put down in the book nothing I can't teach the crew," and it is said that every member of his crew including the cook could take a lunar observation and plot the ship's position.

Bowditch made a total of five trips to sea, over a period of about nine years, his last as master and part owner of the three-masted *Putnam*. Homeward bound from a 13-month voyage to Sumatra and the Ile de France (now called Mauritius) the *Putnam* approached Salem harbor on December 25, 1803, during a thick fog without having had a celestial observation since noon on the 24th. Relying upon his dead reckoning, Bowditch conned his wooden-hulled ship to the entrance of the rocky harbor, where he had the good fortune to get a momentary glimpse of Eastern Point, Cape Ann, enough to confirm his position. The *Putnam* proceeded in, past such hazards as "Bowditch's Ledge" (named after a great-grandfather who had wrecked his ship on the rock more than a century before) and anchored safely at 1900 that evening. Word of the daring feat, performed when other masters were hove-to outside the harbor, spread along the coast and added greatly to Bowditch's reputation. He was, indeed, the "practical navigator."

His standing as a mathematician and successful shipmaster earned him a lucrative (for those times) position ashore within a matter of weeks after his last voyage. He was installed as president of a Salem fire and marine insurance company at the age of 30, and during the 20 years he held that position the company prospered. In 1823 he left Salem to take a similar position with a Boston insurance firm, serving that company with equal success until his death.

From the time he finished the "*Navigator*" until 1814, Bowditch's mathematical and scientific pursuits consisted of studies and papers on the orbits of comets, applications of Napier's rules, magnetic variation, eclipses, calculations on tides, and the charting of Salem harbor. In that year, however, he turned to what he considered the greatest work of his life, the translation into English of *Mecanique Celeste*, by Pierre Laplace. *Mecanique Celeste* was a summary of all the then known facts about the workings of the heavens. Bowditch translated four of the five volumes before his death, and published them at his own expense. He gave many formula derivations which Laplace had not shown, and also included further discoveries following the time of publication. His work made this information available to American astronomers and enabled them to pursue their studies on the basis of that which was already known. Continuing his style of writing for the learner, Bowditch presented his English version of *Mecanique Celeste* in such a manner that the student of mathematics could easily trace the steps involved in reaching the most complicated conclusions.

Shortly after the publication of *The New American Practical Navigator*, Harvard College honored its author with the presentation of the honorary degree of Master of Arts, and in 1816 the college made him an honorary Doctor of Laws. From the time the Harvard graduates of Salem first assisted him in his studies, Bowditch had a great interest in that college, and in 1810 he was elected one of its Overseers, a position he held until 1826, when he was elected to the Corporation. During 1826-27 he was the leader of a small group of men who saved the school from financial disaster by forcing necessary economies on the college's reluctant president. At one time Bowditch was offered a Professorship in Mathematics at Harvard but this, as well as similar offers from West Point and the University of Virginia, he declined. In all his life he was never known to have made a public speech or to have addressed any large group of people.

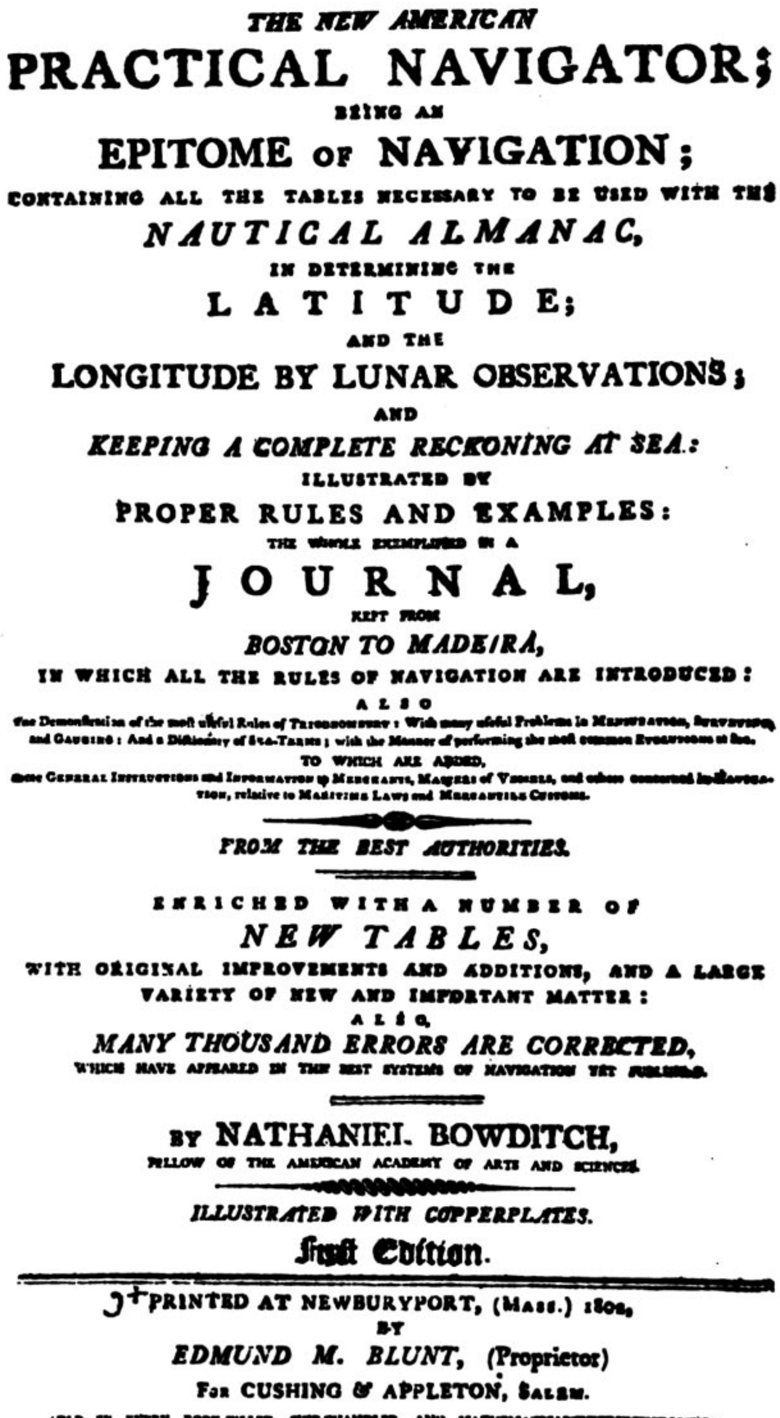
Many other honors came to Bowditch in recognition of his astronomical, mathematical, and marine accomplishments. He became a member of the American Academy of Arts and Sciences, the East India Marine Society, the Royal Academy of Edinburgh, the Royal Society of London, the Royal Irish Academy, the American Philosophical Society, the Connecticut Academy of Arts and Sciences, the Boston Marine Society, the Royal Astronomical Society, the Palermo Academy of Science, and the Royal Academy of Berlin.

Nathaniel Bowditch outlived all of his brothers and sisters by nearly 30 years. Death came to him on March 16,

1838, in his sixty-fifth year. The following eulogy by the Salem Marine Society indicates the regard in which this distinguished American was held by his contemporaries:

"In his death a public, a national, a human benefactor has departed. Not this community, nor our country only, but the whole world, has reason to do honor to his memory. When the voice of Eulogy shall be still, when the tear of Sorrow shall cease to flow, no monument will be needed to keep alive his memory among men; but as long as ships shall sail, the needle point to the north, and the stars go through their wonted courses in the heavens, the name of Dr. Bowditch will be revered as of one who helped his fellow-men in a time of need, who was and is a guide to them over the pathless ocean, and of one who forwarded the great interests of mankind."

The New American Practical Navigator was revised by Nathaniel Bowditch several times after 1802 for subsequent editions of the book. After his death, Jonathan Ingersoll Bowditch, a son who made several voyages, took up the work and his name appeared on the title page from the eleventh edition through the thirty-fifth, in 1867. In 1868 the newly organized U.S. Navy Hydrographic Office bought the copyright. Revisions have been made from time to time to keep the work in step with navigational improvements. The name has been altered to the *American Practical Navigator*, but the book is still commonly known as "Bowditch." A total of more than 900,000 copies has been printed in about 75 editions during the nearly two centuries since the book was first published in 1802. It has lived because it has combined the best techniques of each generation of navigators, who have looked to it as their final authority.


THE NEW AMERICAN

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JOURNAL,

KEPT FROM

BOSTON TO MADEIRA,

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ALSO

The Demonstration of the most useful Rules of TRIGONOMETRY: With many useful Problems in MENSURATION, SURVEYING, and GAUGING: And a Dictionary of SEA-TERMS; with the Manner of performing the most common EVOLUTIONS at Sea.

TO WHICH ARE ADDED,

Some GENERAL INSTRUCTIONS and INFORMATION to MERCHANTS, MASTERS of VESSELS, and others concerned in NAVIGATION, relative to MARITIME LAWS and MERCANTILE CUSTOMS.

FROM THE BEST AUTHORITIES.

ENRICHED WITH A NUMBER OF

NEW TABLES,

WITH ORIGINAL IMPROVEMENTS AND ADDITIONS, AND A LARGE VARIETY OF NEW AND IMPORTANT MATTER:

ALSO,

MANY THOUSAND ERRORS ARE CORRECTED,

WHICH HAVE APPEARED IN THE BEST SYSTEMS OF NAVIGATION YET PUBLISHED.

BY NATHANIEL BOWDITCH,

FELLOW OF THE AMERICAN ACADEMY OF ARTS AND SCIENCES.

ILLUSTRATED WITH COPPERPLATES.

First Edition.

PRINTED AT NEWBURYPORT, (MASS.) 1802,

BY

EDMUND M. BLUNT, (Proprietor)

FOR CUSHING & APPLETON, SALEM.

SOLD BY EVERY BOOKSELLER, SHIP-CHANDLER, AND MATHEMATICAL INSTRUMENT-MAKER, IN THE UNITED STATES AND WEST-INDIES

Original title page of *The New American Practical Navigator,* First Edition, published in 1802.

PREFACE

The Naval Observatory library in Washington, D.C., is unnaturally quiet. It is a large circular room, filled with thousands of books. Its acoustics are perfect; a mere whisper from the room's open circular balcony can be easily heard by those standing on the ground floor. A fountain in the center of the ground floor softly breaks the room's silence as its water stream slowly splashes into a small pool. A library clerk will lead you into a small antechamber where there is a vault containing the Observatory's most rare books. In this vault, one can find an original 1802 first edition of the *New American Practical Navigator*.

One cannot hold this small, delicate, slipcovered book without being impressed by the nearly 200-year unbroken chain of publication that it has enjoyed. It sailed on U.S. merchantmen shortly after the quasi-war with France and during British impressment of merchant seamen that led to the War of 1812. It sailed on U.S. Naval vessels during operations against Mexico in the 1840's, on ships of both the Union and Confederate fleets during the Civil War, and with the U.S. Navy in Cuba in 1898. It went with the Great White Fleet around the world, across the North Atlantic to Europe during both World Wars, to Asia during the Korean and Vietnam Wars, and to the Middle East during Operation Desert Storm.

As navigational requirements and procedures have changed throughout the years, *Bowditch* has changed with them. Originally devoted almost exclusively to celestial navigation, it now also covers a host of modern topics. It is as practical today as it was when Nathaniel Bowditch, master of the *Putnam*, gathered the crew on deck and taught them the mathematics involved in calculating lunar distances. It is that practicality that has been the publication's greatest strength. It is that practicality that makes the publication as useful today as it was in the age of sail.

Seafarers have long memories. In no other profession is tradition more closely guarded. Even the oldest and most cynical acknowledge the special bond that connects those who have made their livelihood plying the sea. This bond is not comprised of a single strand; rather, it is a rich and varied tapestry that stretches from the present back to the birth of our nation and its seafaring culture. As this book is a part of that tapestry, it should not be lightly regarded; rather, it should be preserved, as much for its historical importance as for its practical utility.

Since antiquity, mariners have gathered available navigation information and put it into a text for others to follow. One of the first attempts at this involved volumes of Spanish and Portuguese navigational manuals translated into English between about 1550 to 1750. Writers and translators of the time "borrowed" freely in compiling navigational texts, a practice which continues today with works such as Sailing Directions and Pilots.

Colonial and early American navigators depended exclusively on English navigation texts because there were no American editions. The first American navigational text, *Orthodoxal Navigation*, was completed by Benjamin Hubbard in 1656. The first American navigation text published in America was Captain Thomas Truxton's *Remarks, Instructions, and Examples Relating to the Latitude and Longitude; also the Variation of the Compass, Etc., Etc.*, published in 1794.

The most popular navigational text of the late 18th century was John Hamilton Moore's *The New Practical Navigator*. Edmund M. Blunt, a Newburyport publisher, decided to issue a revised copy of this work for American navigators. Blunt convinced Nathaniel Bowditch, a locally famous mariner and mathematician, to revise and update *The New Practical Navigator*. Several other men also assisted in the revision. Blunt's *The New Practical Navigator* was published in 1799. Blunt also published a second American edition of Hamilton's book in 1800.

By 1802, when Blunt was ready to publish a third edition, Nathaniel Bowditch and others had corrected so many errors in Hamilton's work that Blunt decided to issue the work as a first edition of the *New American Practical Navigator*. It is to that 1802 work that the current edition of the *American Practical Navigator* traces its pedigree.

The *New American Practical Navigator* stayed in the Bowditch and Blunt family until the government bought the copyright in 1867. Edmund M. Blunt published the book until 1833; upon his retirement, his sons, Edmund and George, took over publication.The elder Blunt died in 1862; his son Edmund followed in 1866. The next year, 1867, George Blunt sold the copyright to the government for $25,000. The government has published *Bowditch* ever since. George Blunt died in 1878.

Nathaniel Bowditch continued to correct and revise the book until his death in 1838. Upon his death, the editorial responsibility for the *American Practical Navigator* passed to his son, J. Ingersoll Bowditch. Ingersoll Bowditch continued editing the *Navigator* until George Blunt sold the copyright to the government. He outlived all of the principals involved in publishing and editing the *Navigator*, dying in 1889.

The U.S. government has published some 52 editions since acquiring the copyright to the book that has come to be known simply by its original author's name, "*Bowditch*". Since the government began production, the book has been known by its year of publishing, instead of by the edi-

tion number. During a revision in 1880 by Commander Phillip H. Cooper, USN, the name was changed to *American Practical Navigator*. Bowditch's original method of taking "lunars" was finally dropped from the book in 1914. After several more minor revisions and printings, *Bowditch* was extensively revised between 1946 and 1958.

The present volume, while retaining the basic format of the 1958 version, reorganizes the subjects, deletes obsolete text, and adds new material to keep pace with the extensive changes in navigation that have taken place in the electronic age.

This 1995 edition of the *American Practical Navigator* incorporates extensive changes in organization, format, and content. Recent advances in navigational electronics, communications, positioning, and other technologies have transformed the way navigation is practiced at sea, and it is clear that even more changes are forthcoming. The changes to this edition of BOWDITCH are intended to ensure that this publication remains the premier reference work for practical marine navigation. Concerted efforts were made to return to Nathaniel Bowditch's original intention "to put down in the book nothing I can't teach the crew." To this end, many complex formulas and equations have been eliminated, and emphasis placed on the capabilities and limitations of various navigation systems and how to use them, instead of explaining complex technical and theoretical details. This edition replaces but does not cancel former editions, which may be retained and consulted as to navigation methods not discussed herein.

The former Volume II has been incorporated into this volume to save space and production cost. A larger page size has also been chosen for similar reasons. These two changes allow us to present a single, comprehensive navigation science reference which explains modern navigational methods while respecting traditional ones. The goal of the changes is to put as much useful information before the navigator as possible in the most understandable and readable format.

TAB 1, FUNDAMENTALS, has been reorganized to include an overview of the types and phases of marine navigation and the organizations which support and regulate it. It includes chapters relating to the structure, use and limitations of nautical charts; chart datums and their importance; and other material of a basic nature. The former chapter on the history of navigation has been largely removed. Historical facts are included in the text where necessary to explain present practices or conventions.

TAB 2, PILOTING, now emphasizes the practical aspects of navigating a vessel in restricted waters.

TAB 3, ELECTRONIC NAVIGATION, returns to the position it held in the 1958 edition. Electronic systems are now the primary means of positioning of the modern navigator. Chapters deal with each of the several electronic methods of navigation, organized by type.

TAB 4, CELESTIAL NAVIGATION, has been streamlined and updated. The text in this section contains updated examples and problems and a completely re-edited sight reduction chapter. Extracts from necessary tables have been added to the body of the text for easier reference.

TAB 5, NAVIGATIONAL MATHEMATICS, includes chapters relating to such topics as basic navigational mathematics and computer use in the solution of navigation problems.

TAB 6, NAVIGATIONAL SAFETY, discusses aspects of the new distress and safety communications systems now in place or being implemented in the next several years, as well as navigation regulations, emergency navigation procedures, and distress communications.

TAB 7, OCEANOGRAPHY, is updated and consolidated, but largely unchanged from the former edition.

TAB 8, MARINE METEOROLOGY, (formerly WEATHER) incorporates new weather routing and forecasting methods and material from former appendices. Included are new color plates of the Beaufort Sea States (Courtesy of Environment Canada).

The Glossary has been extensively edited and updated with modern navigational terms, including computer terminology.

This edition was produced largely electronically from start to finish, using the latest in publishing software and data transfer techniques to provide a very flexible production system. This ensures not only that this book is the most efficiently produced ever, but also that it can be easily updated and improved when it again becomes dated, as it surely will.

The masculine pronoun "he" used throughout is meant to refer to both genders.

This book may be kept corrected using the Notice to Mariners and Summary of Corrections. Suggestions and comments for changes and additions may be sent to:

MARINE NAVIGATION DEPARTMENT
ST D 44
NATIONAL IMAGERY AND MAPPING AGENCY
4600 SANGAMORE ROAD
BETHESDA, MD 20816-5003

This book could not have been produced without the expertise of dedicated personnel from many organizations, among them: U.S. Coast Guard, U.S. Naval Academy, U.S. Naval Oceanographic Office, Fleet Training Center (Norfolk), Fleet Numerical Meteorology and Oceanography Center (Monterey), the U.S. Naval Observatory, U.S. Merchant Marine Academy, U.S. Coast and Geodetic Survey, the National Ocean Service, and the National Weather Service. In addition to official government expertise, we appreciate the contributions of private organizations, in particular the Institute of Navigation, and other organizations and individuals too numerous to mention by name. Mariners worldwide can be grateful for the experience, dedication, and professionalism of the people who generously gave their time in this effort.

THE EDITORS

CHAPTER 1

INTRODUCTION TO MARINE NAVIGATION

DEFINITIONS

100. The Art And Science Of Navigation

Marine navigation blends both science and art. A good navigator gathers information from every available source, evaluates this information, determines a fix, and compares that fix with his pre-determined “dead reckoning” position. A navigator constantly evaluates the ship’s position, anticipates dangerous situations well before they arise, and always keeps “ahead of the vessel.” The modern navigator must also understand the basic concepts of the many navigation systems used today, evaluate their output’s accuracy, and arrive at the best possible navigational decisions.

Navigation methods and techniques vary with the type of vessel, the conditions, and the navigator’s experience. Navigating a pleasure craft, for example, differs from navigating a container ship. Both differ from navigating a naval vessel. The navigator uses the methods and techniques best suited to the vessel and conditions at hand.

Some important elements of successful navigation cannot be acquired from any book or instructor. The *science* of navigation can be taught, but the *art* of navigation must be developed from experience.

101. Types Of Navigation

Methods of navigation have changed through history. Each new method has enhanced the mariner’s ability to complete his voyage safely and expeditiously. One of the most important judgments the navigator must make involves choosing the best method to use. Commonly recognized types of navigation are listed below.

- **Dead reckoning (DR)** determines position by advancing a known position for courses and distances. A position so determined is called a dead reckoning (DR) position. It is generally accepted that only course and speed determine the DR position. Correcting the DR position for leeway, current effects, and steering error result in an **estimated position (EP)**. An inertial navigator develops an extremely accurate EP.

- **Piloting** involves navigating in restricted waters with frequent determination of position relative to geographic and hydrographic features.

- **Celestial navigation** involves reducing celestial measurements to lines of position using tables, spherical trigonometry, and almanacs. It is used primarily as a backup to satellite and other electronic systems in the open ocean.

- **Radio navigation** uses radio waves to determine position by either radio direction finding systems or hyperbolic systems.

- **Radar navigation** uses radar to determine the distance from or bearing of objects whose position is known. This process is separate from radar’s use as a collision avoidance system.

- **Satellite navigation** uses artificial earth satellites for determination of position.

Electronic integrated bridge concepts are driving future navigation system planning. Integrated systems take inputs from various ship sensors, electronically display positioning information, and provide control signals required to maintain a vessel on a preset course. The navigator becomes a system manager, choosing system presets, interpreting system output, and monitoring vessel response.

In practice, a navigator synthesizes different methodologies into a single integrated system. He should never feel comfortable utilizing only one method when others are available for backup. Each method has advantages and disadvantages. The navigator must choose methods appropriate to each particular situation.

With the advent of automated position fixing and electronic charts, modern navigation is almost completely an electronic process. The mariner is constantly tempted to rely solely on electronic systems. This would be a mistake. Electronic navigation systems are always subject to failure, and the professional mariner must never forget that the safety of his ship and crew may depend on skills that differ little from those practiced generations ago. Proficiency in conventional piloting and celestial navigation remains essential.

102. Phases Of Navigation

Four distinct phases define the navigation process. The

mariner should choose the system mix that meets the accuracy requirements of each phase.

- **Inland Waterway Phase**: Piloting in narrow canals, channels, rivers, and estuaries.
- **Harbor/Harbor Approach Phase**: Navigating to a harbor entrance and piloting in harbor approach channels.
- **Coastal Phase**: Navigating within 50 miles of the coast or inshore of the 200 meter depth contour.
- **Ocean Phase**: Navigating outside the coastal area in the open sea.

The navigator's position accuracy requirements, his fix interval, and his systems requirements differ in each phase. The following table can be used as a general guide for selecting the proper system(s).

	Inland Waterway	*Harbor/Harbor Approach*	*Coastal*	*Ocean*
DR	X	X	X	X
Piloting	X	X	X	
Celestial			X	X
Radio		X	X	X
Radar	X	X	X	
Satellite	X*	X	X	X

Table 102. The relationship of the types and phases of navigation.
* Differential GPS may be used if available.

NAVIGATIONAL TERMS AND CONVENTIONS

103. Important Conventions And Concepts

Throughout the history of navigation, numerous terms and conventions have been established which enjoy worldwide recognition. The professional navigator, to gain a full understanding of his field, should understand the origin of certain terms, techniques, and conventions. The following section discusses some of the important ones.

Defining a **prime meridian** is a comparatively recent development. Until the beginning of the 19th century, there was little uniformity among cartographers as to the meridian from which to measure longitude. This did not lead to any problem because there was no widespread method for determining longitude accurately.

Ptolemy, in the 2nd century AD, measured longitude eastward from a reference meridian 2 degrees west of the Canary Islands. In 1493, Pope Alexander VI established a line in the Atlantic west of the Azores to divide the territories of Spain and Portugal. For many years, cartographers of these two countries used this dividing line as the prime meridian. In 1570 the Dutch cartographer Ortelius used the easternmost of the Cape Verde Islands. John Davis, in his 1594 *The Seaman's Secrets,* used the Isle of Fez in the Canaries because there the variation was zero. Mariners paid little attention to these conventions and often reckoned their longitude from several different capes and ports during a voyage.

The meridian of London was used as early as 1676, and over the years its popularity grew as England's maritime interests increased. The system of measuring longitude both east and west through 180° may have first appeared in the middle of the 18th century. Toward the end of that century, as the Greenwich Observatory increased in prominence, English cartographers began using the meridian of that observatory as a reference. The publication by the Observatory of the first British Nautical Almanac in 1767 further entrenched Greenwich as the prime meridian. An unsuccessful attempt was made in 1810 to establish Washington, D.C. as the prime meridian for American navigators and cartographers. In 1884, the meridian of Greenwich was officially established as the prime meridian. Today, all maritime nations have designated the Greenwich meridian the prime meridian, except in a few cases where local references are used for certain harbor charts.

Charts are graphic representations of areas of the earth for use in marine or air navigation. Nautical charts depict features of particular interest to the marine navigator. Charts have probably existed since at least 600 BC. Stereographic and orthographic projections date from the 2nd century BC. In 1569 Gerardus Mercator published a chart

using the mathematical principle which now bears his name. Some 30 years later, Edward Wright published corrected mathematical tables for this projection, enabling cartographers to produce charts on the Mercator projection. This projection is still widely in use.

Sailing directions or **pilots** have existed since at least the 6th century BC. Continuous accumulation of navigational data, along with increased exploration and trade, led to increased production of volumes through the Middle Ages. “Routiers” were produced in France about 1500; the English referred to them as “rutters.” In 1584 Lucas Waghenaer published the *Spieghel der Zeevaerdt (The Mariner’s Mirror)*, which became the model for such publications for several generations of navigators. They were known as “Waggoners” by most sailors. Modern pilots and sailing directions are based on extensive data collection and compilation efforts begun by Matthew Fontaine Maury beginning in 1842.

The **compass** was developed about 1000 years ago. The origin of the magnetic compass is uncertain, but Norsemen used it in the 11th century. It was not until the 1870s that Lord Kelvin developed a reliable dry card marine compass. The fluid-filled compass became standard in 1906.

Variation was not understood until the 18th century, when Edmond Halley led an expedition to map lines of variation in the South Atlantic. **Deviation** was understood at least as early as the early 1600s, but correction of compass error was not possible until Matthew Flinders discovered that a vertical iron bar could reduce errors. After 1840, British Astronomer Royal Sir George Airy and later Lord Kelvin developed combinations of iron masses and small magnets to eliminate most magnetic compass error.

The **gyrocompass** was made necessary by iron and steel ships. Leon Foucault developed the basic gyroscope in 1852. An American (Elmer Sperry) and a German (Anshutz Kampfe) both developed electrical gyrocompasses in the early years of the 20th century.

The **log** is the mariner’s speedometer. Mariners originally measured speed by observing a chip of wood passing down the side of the vessel. Later developments included a wooden board attached to a reel of line. Mariners measured speed by noting how many knots in the line unreeled as the ship moved a measured amount of time; hence the term **knot.** Mechanical logs using either a small paddle wheel or a rotating spinner arrived about the middle of the 17th century. The taffrail log still in limited use today was developed in 1878. Modern logs use electronic sensors or spinning devices that induce small electric fields proportional to a vessel’s speed. An engine revolution counter or shaft log often measures speed onboard large ships. Doppler speed logs are used on some vessels for very accurate speed readings. Inertial and satellite systems also provide highly accurate speed readings.

The Metric Conversion Act of 1975 and the Omnibus Trade and Competitiveness Act of 1988 established the **metric system** of weights and measures in the United States. As a result, the government is converting charts to the metric format. Considerations of expense, safety of navigation, and logical sequencing will require a conversion effort spanning many years. Notwithstanding the conversion to the metric system, the common measure of distance at sea is the **nautical mile**.

The current policy of the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) and the National Ocean Service (NOS) is to convert new compilations of nautical, special purpose charts, and publications to the metric system. This conversion began on January 2, 1970. Most modern maritime nations have also adopted the meter as the standard measure of depths and heights. However, older charts still on issue and the charts of some foreign countries may not conform to this standard.

The **fathom** as a unit of length or depth is of obscure origin. Posidonius reported a sounding of more than 1,000 fathoms in the 2nd century BC. How old the unit was then is unknown. Many modern charts are still based on the fathom, as conversion to the metric system continues.

The sailings refer to various methods of mathematically determining course, distance, and position. They have a history almost as old as mathematics itself. Thales, Hipparchus, Napier, Wright, and others contributed the formulas that permit computation of course and distance by plane, traverse, parallel, middle latitude, Mercator, and great circle sailings.

104. The Earth

The earth is an oblate spheroid (a sphere flattened at the poles). Measurements of its dimensions and the amount of its flattening are subjects of geodesy. However, for most navigational purposes, assuming a spherical earth introduces insignificant error. The earth’s axis of rotation is the line connecting the North Pole and the South Pole.

A **great circle** is the line of intersection of a sphere and a plane through its center. This is the largest circle that can be drawn on a sphere. The shortest line on the surface of a sphere between two points on the surface is part of a great circle. On the spheroidal earth the shortest line is called a **geodesic**. A great circle is a near enough approximation to a geodesic for most problems of navigation. A **small circle** is the line of intersection of a sphere and a plane which does not pass through the center. See Figure 104a.

The term **meridian** is usually applied to the **upper branch** of the half-circle from pole to pole which passes through a given point. The opposite half is called the **lower branch.**

A **parallel** or parallel of latitude is a circle on the surface of the earth parallel to the plane of the equator. It connects all points of equal latitude. The equator is a great circle at latitude 0°. See Figure 104b. The poles are single points at latitude 90°. All other parallels are small circles.

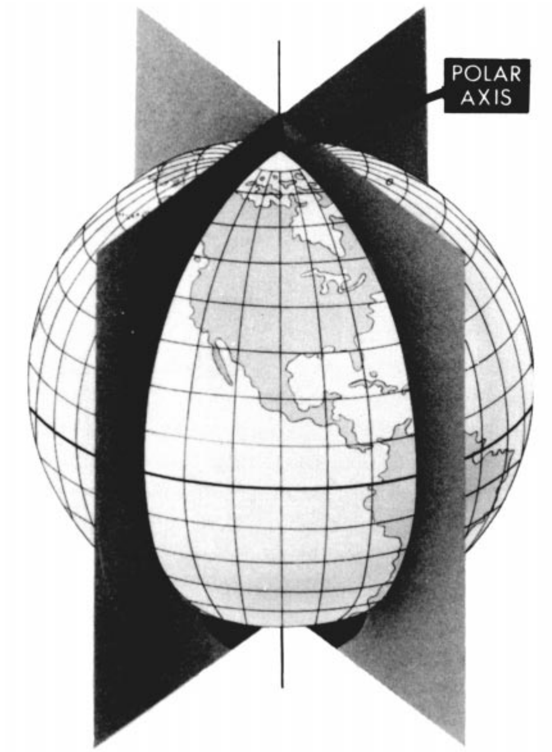


Figure 104a. The planes of the meridians at the polar axis.

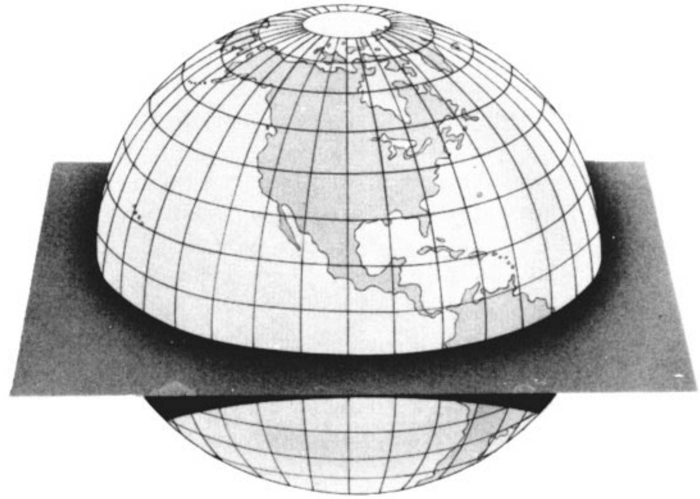


Figure 104b. The equator is a great circle midway between the poles.

105. Coordinates

Coordinates, termed **latitude** and **longitude**, can define any position on earth. **Latitude (L, lat.)** is the angular distance from the equator, measured northward or southward along a meridian from 0° at the equator to 90° at the poles. It is designated north (N) or south (S) to indicate the direction of measurement.

The **difference of latitude (*l*, DLat.)** between two places is the angular length of arc of any meridian between their parallels. It is the numerical difference of the latitudes if the places are on the same side of the equator; it is the sum of the latitudes if the places are on opposite sides of the equator. It may be designated north (N) or south (S) when appropriate. The middle or **mid-latitude (Lm)** between two places on the same side of the equator is half the sum of their latitudes. Mid-latitude is labeled N or S to indicate whether it is north or south of the equator.

The expression may refer to the mid-latitude of two places on opposite sides of the equator. In this case, it is equal to half the difference between the two latitudes and takes the name of the place farthest from the equator. However, this usage is misleading because it lacks the significance usually associated with the expression. When the places are on opposite sides of the equator, two mid-latitudes are generally used. Calculate these two mid-latitudes by averaging each latitude and 0°.

Longitude (l, long.) is the angular distance between the prime meridian and the meridian of a point on the earth, measured eastward or westward from the prime meridian through 180°. It is designated east (E) or west (W) to indicate the direction of measurement.

The **difference of longitude (DLo)** between two places is the shorter arc of the parallel or the smaller angle at the pole between the meridians of the two places. If both places are on the same side (east or west) of Greenwich, DLo is the numerical difference of the longitudes of the two places; if on opposite sides, DLo is the numerical sum unless this exceeds 180°, when it is 360° minus the sum. The distance between two meridians at any parallel of latitude, expressed in distance units, usually nautical miles, is called **departure (p, Dep.)**. It represents distance made good east or west as a craft proceeds from one point to another. Its numerical value between any two meridians decreases with increased latitude, while DLo is numerically the same at any latitude. Either DLo or p may be designated east (E) or west (W) when appropriate.

106. Distance On The Earth

Distance, as used by the navigator, is the length of the **rhumb line** connecting two places. This is a line making the same angle with all meridians. Meridians and parallels which also maintain constant true directions may be con-

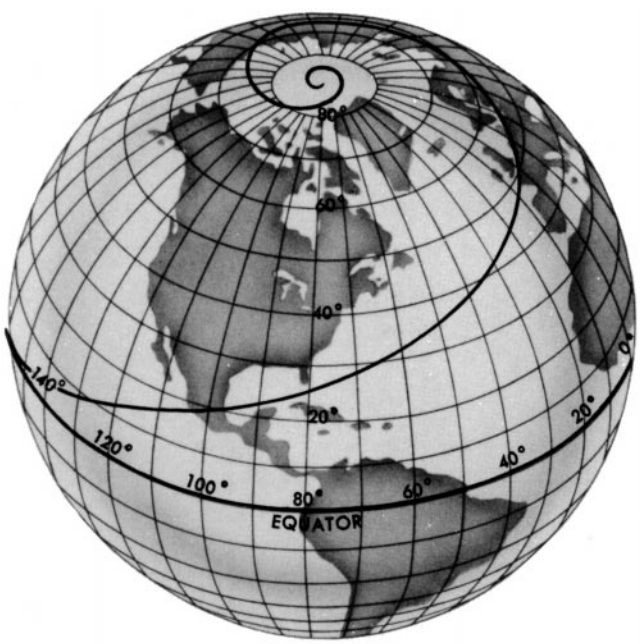


Figure 106. A loxodrome.

sidered special cases of the rhumb line. Any other rhumb line spirals toward the pole, forming a **loxodromic curve** or **loxodrome**. See Figure 106. Distance along the great circle connecting two points is customarily designated **great-circle distance**. For most purposes, considering the nautical mile the length of one minute of latitude introduces no significant error.

Speed (S) is rate of motion, or distance per unit of time. A **knot (kn.)**, the unit of speed commonly used in navigation, is a rate of 1 nautical mile per hour. The expression **speed of advance (SOA)** is used to indicate the speed to be made along the intended track. **Speed over the ground (SOG)** is the actual speed of the vessel over the surface of the earth at any given time. To calculate **speed made good (SMG)** between two positions, divide the distance between the two positions by the time elapsed between the two positions.

107. Direction On The Earth

Direction is the position of one point relative to another. Navigators express direction as the angular difference in degrees from a reference direction, usually north or the ship's head. **Course (C, Cn)** is the horizontal direction in which a vessel is steered or intended to be steered, expressed as angular distance from north clockwise through 360°. Strictly used, the term applies to direction through the water, not the direction intended to be made good over the ground.

The course is often designated as true, magnetic, compass, or grid according to the reference direction. **Track made good (TMG)** is the single resultant direction from the point of departure to point of arrival at any given time. **Course of advance (COA)** is the direction intended to be made good over the ground, and **course over ground (COG)** is the direction between a vessel's last fix and an EP. A course line is a line drawn on a chart extending in the direction of a course. It is sometimes convenient to express a course as an angle from either north or south, through 90° or 180°. In this case it is designated course angle (C) and should be properly labeled to indicate the origin (prefix) and direction of measurement (suffix). Thus, C N35°E = Cn 035° (000° + 35°), C N155°W = Cn 205° (360° - 155°), C S47°E = Cn 133° (180° - 47°). But Cn 260° may be either C N100°W or C S80°W, depending upon the conditions of the problem.

Track (TR) is the intended horizontal direction of travel with respect to the earth. The terms intended track and trackline are used to indicate the path of intended travel. See Figure 107a. The track consists of one or a series of course lines, from the point of departure to the destination, along which it is intended to proceed. A great circle which a vessel intends to follow is called a **great-circle track**, though it consists of a series of straight lines approximating a great circle.

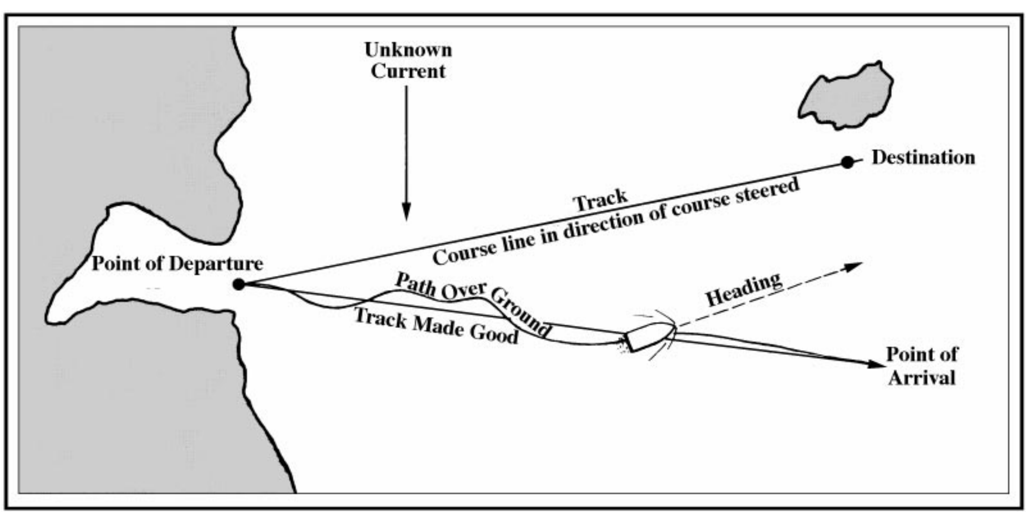


Figure 107a. Course line, track, track made good, and heading.

Heading (Hdg., SH) is the direction in which a vessel is pointed, expressed as angular distance from 000° clockwise through 360°. Do not confuse heading and course. Heading constantly changes as a vessel yaws back and forth across the course due to sea, wind, and steering error.

Bearing (B, Brg.) is the direction of one terrestrial point from another, expressed as angular distance from 000° (North) clockwise through 360°. When measured through 90° or 180° from either north or south, it is called bearing angle (B). Bearing and azimuth are sometimes used interchangeably, but the latter more accurately refers to the horizontal direction of a point on the celestial sphere from a point on the earth. A relative bearing is measured relative to the ship's heading from 000° (dead ahead) clockwise through 360°. However, it is sometimes conveniently measured right or left from 0° at the ship's head through 180°. This is particularly true when using the table for Distance of an Object by Two Bearings.

To convert a relative bearing to a true bearing, add the true heading:

True Bearing = Relative Bearing + True Heading.
Relative Bearing = True Bearing – True Heading.

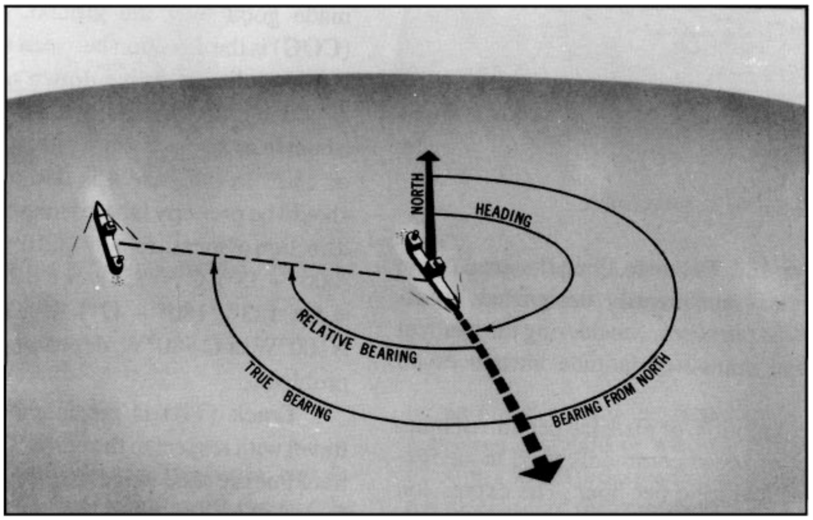


Figure 107b. Relative Bearing.

DEVELOPMENT OF NAVIGATION

108. Latitude And Longitude Determination

Navigators have made latitude observations for thousands of years. Accurate sun declination tables have been published for centuries, enabling experienced seamen to compute latitude to within 1 or 2 degrees. Mariners still use meridian observations of the sun and highly refined ex-meridian techniques. Those who today determine their latitude by measuring the altitude of Polaris are using a method well known to 15th century navigators.

A method of finding longitude eluded mariners for centuries. Several solutions independent of time proved too cumbersome. The lunar distance method, which determines GMT by observing the moon's position among the stars, became popular in the 1800s. However, the mathematics required by most of these processes were far above the abilities of the average seaman. It was apparent that the solution lay in keeping accurate time at sea.

In 1714, the British Board of Longitude was formed, offering a small fortune in reward to anyone who could provide a solution to the problem.

An Englishman, John Harrison, responded to the challenge, developing four chronometers between 1735 and 1760. The most accurate of these timepieces lost only 15 seconds on a 156 day round trip between London and Barbados. The Board, however, paid him only half the promised reward. The King finally intervened on Harrison's behalf, and Harrison received his full reward of £20,000 at the advanced age of 80.

Rapid chronometer development led to the problem of determining **chronometer error** aboard ship. **Time balls**, large black spheres mounted in port in prominent locations, were dropped at the stroke of noon, enabling any ship in harbor which could see the ball to determine chronometer error. By the end of the U.S. Civil War, telegraph signals were being used to key time balls. Use of radio signals to send time ticks to ships well offshore began in 1904, and soon worldwide signals were available.

109. The Navigational Triangle

Modern celestial navigators reduce their celestial observations by solving a **navigational triangle** whose points are the elevated pole, the celestial body, and the zenith of the observer. The sides of this triangle are the polar distance of the body (**codeclination**), its zenith distance (**coaltitude**), and the polar distance of the zenith (**colatitude** of the observer).

A spherical triangle was first used at sea in solving **lunar distance** problems. Simultaneous observations were made of the altitudes of the moon and the sun or a star near the ecliptic and the angular distance between the moon and the other body. The zenith of the observer and the two celestial bodies formed the vertices of a triangle whose sides were the two coaltitudes and the angular distance between the bodies. Using a mathematical calculation the navigator "cleared" this distance of the effects of refraction and parallax applicable to each altitude. This corrected value was then used as an argument for entering the almanac. The almanac gave the true lunar distance from the sun and several stars at 3 hour intervals. Previously, the navigator had set his watch or checked its error and rate with the local mean time determined by celestial observations. The local mean time of the watch, properly corrected, applied to the Greenwich mean time obtained from the lunar distance observation, gave the longitude.

The calculations involved were tedious. Few mariners could solve the triangle until Nathaniel Bowditch published his simplified method in 1802 in *The New American Practical Navigator*.

Reliable chronometers were available in 1802, but their high cost precluded their general use aboard most ships. However, most navigators could determine their longitude using Bowditch's method. This eliminated the need for parallel sailing and the lost time associated with it. Tables for the lunar distance solution were carried in the American nautical almanac until the second decade of the 20th century.

110. The Time Sight

The theory of the **time sight** had been known to mathematicians since the development of spherical trigonometry, but not until the chronometer was developed could it be used by mariners.

The time sight used the modern navigational triangle. The codeclination, or polar distance, of the body could be determined from the almanac. The zenith distance (coaltitude) was determined by observation. If the colatitude were known, three sides of the triangle were available. From these the meridian angle was computed. The comparison of this with the Greenwich hour angle from the almanac yielded the longitude.

The time sight was mathematically sound, but the navigator was not always aware that the longitude determined was only as accurate as the latitude, and together they merely formed a point on what is known today as a **line of position**. If the observed body was on the prime vertical, the line of position ran north and south and a small error in latitude generally had little effect on the longitude. But when the body was close to the meridian, a small error in latitude produced a large error in longitude.

The line of position by celestial observation was unknown until discovered in 1837 by 30-year-old Captain Thomas H. Sumner, a Harvard graduate and son of a United States congressman from Massachusetts. The discovery of the "**Sumner line**," as it is sometimes called, was considered by Maury "the commencement of a new era in practical navigation." This was the turning point in the development of modern celestial navigation technique. In Sumner's own words, the discovery took place in this manner:

> Having sailed from Charleston, S. C., 25th November, 1837, bound to Greenock, a series of heavy gales from the Westward promised a quick passage; after passing the Azores, the wind prevailed from the Southward, with thick weather; after passing Longitude 21° W, no observation was had until near the land; but soundings were had not far, as was supposed, from the edge of the Bank. The weather was now more boisterous, and very thick; and the wind still Southerly; arriving about midnight, 17th December, within 40 miles, by dead reckoning, of Tusker light; the wind hauled SE, true, making the Irish coast a lee shore; the ship was then kept close to the wind, and several tacks made to preserve her position as nearly as possible until daylight; when nothing being in sight, she was kept on ENE under short sail, with heavy gales; at about 10 AM an altitude of the sun was observed, and the Chronometer time noted; but, having run so far without any observation, it was plain the Latitude by dead reckoning was liable to error, and could not be entirely relied on. Using, however, this Latitude, in finding the Longitude by Chronometer, it was found to put the ship 15' of Longitude E from her position by dead reckoning; which in Latitude 52° N is 9 nautical miles; this seemed to agree tolerably well with the dead reckoning; but feeling doubtful of the Latitude, the observation was tried with a Latitude 10' further N, finding this placed the ship ENE 27 nautical miles, of the former position, it was tried again with a Latitude 20' N of the dead reckoning; this also placed the ship still further ENE, and still 27 nautical miles further; these three positions were then seen to lie in the direction of Small's light.
>
> It then at once appeared that the observed altitude must have happened at all the three points, and at Small's light, and at the ship, at the same instant of time; and it followed, that Small's light must bear ENE, if the Chronometer was right. Having been convinced of this truth, the ship was kept on her course, ENE, the wind being still SE., and in less than an hour, Small's light was made bearing ENE 1/2 E, and close aboard.

In 1843 Sumner published a book, A *New and Accurate Method of Finding a Ship's Position at Sea by Projection on Mercator's Chart*. He proposed solving a single time sight

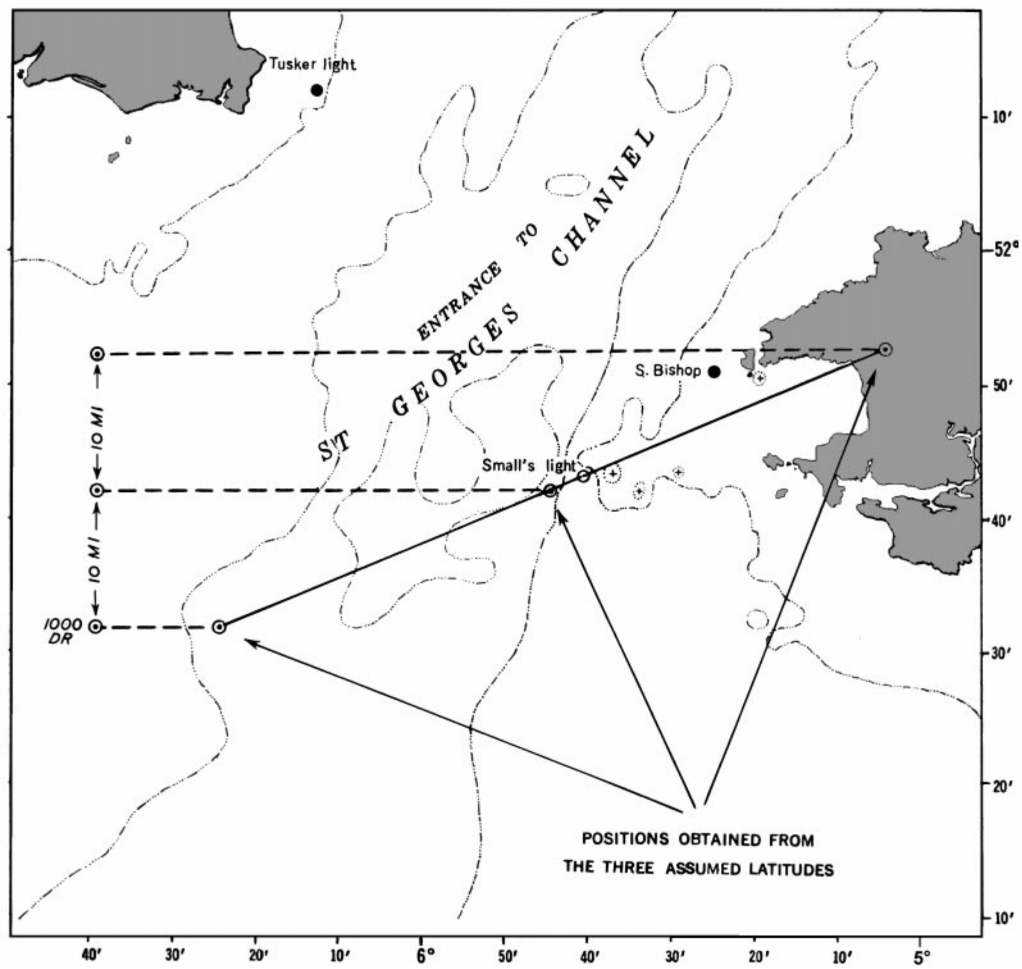


Figure 110. The first celestial line of position, obtained by Captain Thomas Sumner in 1837.

twice, using latitudes somewhat greater and somewhat less than that arrived at by dead reckoning, and joining the two positions obtained to form the line of position.

The Sumner method required the solution of two time sights to obtain each line of position. Many older navigators preferred not to draw the lines on their charts, but to fix their position mathematically by a method which Sumner had also devised and included in his book. This was a tedious but popular procedure.

111. Navigational Tables

Spherical trigonometry is the basis for solving every navigational triangle, and until about 80 years ago the navigator had no choice but to solve each triangle by tedious, manual computations.

Lord Kelvin, generally considered the father of modern navigational methods, expressed interest in a book of tables with which a navigator could avoid tedious trigonometric solutions. However, solving the many thousands of triangles involved would have made the project too costly. Computers finally provided a practical means of preparing tables. In 1936 the first volume of Pub. No. 214 was made available; later, Pub. No. 249 was provided for air navigators. Pub. No. 229, *Sight Reduction Tables for Marine Navigation*, has replaced Pub. No. 214.

Modern calculators are gradually replacing the tables. Scientific calculators with trigonometric functions can easily solve the navigational triangle. Navigational calculators readily solve celestial sights and perform a variety of voyage planning functions. Using a calculator generally gives more accurate lines of position because it eliminates the rounding errors inherent in tabular inspection and interpolation.

112. Electronics And Navigation

Perhaps the first application of electronics to navigation involved sending telegraphic time signals in 1865 to check chronometer error. Transmitting radio time signals for at sea chronometer checks dates to 1904.

Radio broadcasts providing navigational warnings, begun in 1907 by the U.S. Navy Hydrographic Office, helped increase the safety of navigation at sea.

By the latter part of World War I the directional properties of a loop antenna were successfully used in the radio

direction finder. The first radiobeacon was installed in 1921. Early 20th century experiments by Behm and Langevin led to the U.S. Navy's development of the first practical echo sounder in 1922.

Today, electronics touches almost every aspect of navigation. Hyperbolic systems, satellite systems, and electronic charts all require an increasingly sophisticated electronics suite. These systems' accuracy and ease of use make them invaluable assets to the navigator. Indeed, it is no exaggeration to state that, with the advent of the electronic chart and differential GPS, the mariner will soon be able to navigate from port to port using electronic navigation equipment alone.

113. Development Of Radar

As early as 1904, German engineers were experimenting with reflected radio waves. In 1922 two American scientists, Dr. A. Hoyt Taylor and Leo C. Young, testing a communication system at the Naval Aircraft Radio Laboratory, noted fluctuations in the signals when ships passed between stations on opposite sides of the Potomac River. In 1935 the British began work on radar. In 1937 the USS Leary tested the first seagoing radar. In 1940 United States and British scientists combined their efforts. When the British revealed the principle of the multicavity magnetron developed by J. T. Randall and H. A. H. Boot at the University of Birmingham in 1939, microwave radar became practical. In 1945, at the close of World War II, radar became available for commercial use.

114. Development Of Hyperbolic Radio Aids

Various hyperbolic systems were developed from World War II, including Loran A. This was replaced by the more accurate Loran C system in use today. Using very low frequencies, the Omega navigation system provides worldwide, though less accurate, coverage for a variety of applications including marine navigation. Various short range and regional hyperbolic systems have been developed by private industry for hydrographic surveying, offshore facilities positioning, and general navigation.

115. Other Electronic Systems

The **Navy Navigation Satellite System (NAVSAT)** fulfilled a requirement established by the Chief of Naval Operations for an accurate worldwide navigation system for all naval surface vessels, aircraft, and submarines. The system was conceived and developed by the Applied Physics Laboratory of The Johns Hopkins University. The underlying concept that led to development of satellite navigation dates to 1957 and the first launch of an artificial satellite into orbit. NAVSAT has been replaced by the far more accurate and widely available **Global Positioning System (GPS)**.

The first **inertial navigation system** was developed in 1942 for use in the V2 missile by the Peenemunde group under the leadership of Dr. Wernher von Braun. This system used two 2-degree-of-freedom gyroscopes and an integrating accelerometer to determine the missile velocity. By the end of World War II, the Peenemunde group had developed a stable platform with three single-degree-of-freedom gyroscopes and an integrating accelerometer. In 1958 an inertial navigation system was used to navigate the USS *Nautilus* under the ice to the North Pole.

NAVIGATION ORGANIZATIONS

116. Governmental Roles

Navigation only a generation ago was an independent process, carried out by the mariner without outside assistance. With compass and charts, sextant and chronometer, he could independently travel anywhere in the world. The increasing use of electronic navigation systems has made the navigator dependent on many factors outside his control. Government organizations fund, operate, and regulate satellites, Loran, and other electronic systems. Governments are increasingly involved in regulation of vessel movements through traffic control systems and regulated areas. Understanding the governmental role in supporting and regulating navigation is vitally important to the mariner. In the United States, there are a number of official organizations which support the interests of navigators. Some have a policy-making role; others build and operate navigation systems. Many maritime nations have similar organizations performing similar functions. International organizations also play a significant role.

117. The Coast And Geodetic Survey

The **U.S. Coast and Geodetic Survey** was founded in 1807 when Congress passed a resolution authorizing a survey of the coast, harbors, outlying islands, and fishing banks of the United States. President Thomas Jefferson appointed Ferdinand Hassler, a Swiss immigrant and professor of mathematics at West Point, the first Director of the "Survey of the Coast." The survey became the "Coast Survey" in 1836.

The approaches to New York were the first sections of the coast charted, and from there the work spread northward and southward along the eastern seaboard. In 1844 the work was expanded and arrangements made to chart simultaneously the gulf and east coasts. Investigation of tidal conditions began, and in 1855 the first tables of tide predictions were published. The California gold rush necessitated

a survey of the west coast. This survey began in 1850, the year California became a state. Coast Pilots, or Sailing Directions, for the Atlantic coast of the United States were privately published in the first half of the 19th century. In 1850 the Survey began accumulating data that led to federally produced Coast Pilots. The 1889 Pacific Coast Pilot was an outstanding contribution to the safety of west coast shipping.

In 1878 the survey was renamed “Coast and Geodetic Survey.” In 1970 the survey became the “National Ocean Survey,” and in 1983 it became the “National Ocean Service.” The Office of Charting and Geodetic Services accomplished all charting and geodetic functions. In 1991 the name was changed back to the original “Coast and Geodetic Survey,” organized under the National Ocean Service along with several other environmental offices. Today it provides the mariner with the charts and coast pilots of all waters of the United States and its possessions, and tide and tidal current tables for much of the world. Its administrative order requires the Coast and Geodetic Survey to plan and direct programs to produce charts and related information for safe navigation of the Nation’s waterways, territorial seas, and national airspace. This work includes all activities related to the National Geodetic Reference System; surveying, charting, and data collection; production and distribution of charts; and research and development of new technologies to enhance these missions.

118. The Defense Mapping Agency

In the first years of the newly formed United States of America, charts and instruments used by the Navy and merchant mariners were left over from colonial days or were obtained from European sources. In 1830 the U.S. Navy established a “Depot of Charts and Instruments” in Washington, D. C. It was a storehouse from which available charts, sailing directions, and navigational instruments were issued to Naval ships. Lieutenant L. M. Goldsborough and one assistant, Passed Midshipman R. B. Hitchcock, constituted the entire staff.

The first chart published by the Depot was produced from data obtained in a survey made by Lieutenant Charles Wilkes, who had succeeded Goldsborough in 1834. Wilkes later earned fame as the leader of a United States expedition to Antarctica. From 1842 until 1861 Lieutenant Matthew Fontaine Maury served as Officer in Charge. Under his command the Depot rose to international prominence. Maury decided upon an ambitious plan to increase the mariner’s knowledge of existing winds, weather, and currents. He began by making a detailed record of pertinent matter included in old log books stored at the Depot. He then inaugurated a hydrographic reporting program among shipmasters, and the thousands of reports received, along with the log book data, were compiled into the “*Wind and Current Chart of the North Atlantic*” in 1847. This is the ancestor of today’s Pilot Chart. The United States instigated an international conference in 1853 to interest other nations in a system of exchanging nautical information. The plan, which was Maury’s, was enthusiastically adopted by other maritime nations. In 1854 the Depot was redesignated the “U.S. Naval Observatory and Hydrographical Office.” In 1861, Maury, a native of Virginia, resigned from the U.S. Navy and accepted a commission in the Confederate Navy at the beginning of the Civil War. This effectively ended his career as a navigator, author, and oceanographer. At war’s end, he fled the country. Maury’s reputation suffered from his embracing the Confederate cause. In 1867, while Maury was still absent from the country to avoid arrest for treason, George W. Blunt, an editor of hydrographic publications, wrote:

> In mentioning what our government has done towards nautical knowledge, I do not allude to the works of Lieutenant Maury, because I deem them worthless. . . . They have been suppressed since the rebellion by order of the proper authorities, Maury’s loyalty and hydrography being alike in quality.

After Maury’s return to the United States in 1868, he served as an instructor at the Virginia Military Institute. He continued at this position until his death in 1873. Since his death, his reputation as one of America’s greatest hydrographers has been restored.

In 1866 Congress separated the Observatory and the Hydrographic Office, broadly increasing the functions of the latter. The Hydrographic Office was authorized to carry out surveys, collect information, and print every kind of nautical chart and publication “for the benefit and use of navigators generally.”

The Hydrographic Office purchased the copyright of ***The New American Practical Navigator*** in 1867. The first Notice to Mariners appeared in 1869. Daily broadcast of navigational warnings was inaugurated in 1907. In 1912, following the sinking of the *Titanic*, the International Ice Patrol was established.

In 1962 the U.S. Navy Hydrographic Office was redesignated the U.S. Naval Oceanographic Office. In 1972 certain hydrographic functions of the latter office were transferred to the **Defense Mapping Agency Hydrographic Center**. In 1978 the **Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC)** assumed hydrographic and topographic chart production functions. DMAHTC provides support to the U.S. Department of Defense and other federal agencies on matters concerning mapping, charting, and geodesy. It continues to fulfill the old Hydrographic Office’s responsibilities to “navigators generally.”

119. The United States Coast Guard

Alexander Hamilton established the **U.S. Coast Guard** as the Revenue Marine, later the Revenue Cutter Service, on August 4, 1790. It was charged with enforcing the customs laws of the new nation. A revenue cutter, the *Harriet Lane*, fired the first shot from a naval unit in the Civil War at Fort Sumter. The Revenue Cutter Service became the U.S. Coast Guard when combined with the Lifesaving Service in 1915. The Lighthouse Service was added in 1939, and the Bureau of Marine Inspection and Navigation was added in 1942. The Coast Guard was transferred from the Treasury Department to the Department of Transportation in 1967.

The primary functions of the Coast Guard include maritime search and rescue, law enforcement, and operation of the nation's aids to navigation system. In addition, the Coast Guard is responsible for port safety and security, merchant marine inspection, and marine pollution control. The Coast Guard operates a large and varied fleet of ships, boats, and aircraft in performing its widely ranging duties.

Navigation systems operated by the Coast Guard include the system of some 40,000 lighted and unlighted beacons, buoys, and ranges in U.S. waters; the U.S. stations of the Loran C system; the Omega navigation system; radiobeacons and racons; differential GPS (DGPS) services in the U.S.; and Vessel Traffic Services (VTS) in major ports and harbors of the U.S.

120. The United States Navy

The **U.S. Navy** was officially established in 1798. Its role in the development of navigational technology has been singular. From the founding of the Naval Observatory to the development of the most advanced electronics, the U.S. Navy has been a leader in developing devices and techniques designed to make the navigator's job safer and easier.

The development of almost every device known to navigation science has been deeply influenced by Naval policy. Some systems are direct outgrowths of specific Naval needs; some are the result of technological improvements shared with other services and with commercial maritime industry.

121. The United States Naval Observatory

One of the first observatories in the United States was built in 1831-1832 at Chapel Hill, N.C. The Depot of Charts and Instruments, established in 1830, was the agency from which the U.S. Navy Hydrographic Office and the **U.S. Naval Observatory** evolved 36 years later. Under Lieutenant Charles Wilkes, the second Officer in Charge, the Depot about 1835 installed a small transit instrument for rating chronometers.

The Mallory Act of 1842 provided for the establishment of a permanent observatory. The director was authorized to purchase everything necessary to continue astronomical study. The observatory was completed in 1844 and the results of its first observations were published two years later. Congress established the Naval Observatory as a separate agency in 1866. In 1873 a refracting telescope with a 26 inch aperture, then the world's largest, was installed. The observatory, located in Washington, D.C., has occupied its present site since 1893.

122. The Royal Greenwich Observatory

England had no early privately supported observatories such as those on the continent. The need for navigational advancement was ignored by Henry VIII and Elizabeth I, but in 1675 Charles II, at the urging of John Flamsteed, Jonas Moore, Le Sieur de Saint Pierre, and Christopher Wren, established the **Greenwich Royal Observatory**. Charles limited construction costs to £500, and appointed Flamsteed the first Astronomer Royal, at an annual salary of £100. The equipment available in the early years of the observatory consisted of two clocks, a "sextant" of 7 foot radius, a quadrant of 3 foot radius, two telescopes, and the star catalog published almost a century before by Tycho Brahe. Thirteen years passed before Flamsteed had an instrument with which he could determine his latitude accurately.

In 1690 a transit instrument equipped with a telescope and vernier was invented by Romer; he later added a vertical circle to the device. This enabled the astronomer to determine declination and right ascension at the same time. One of these instruments was added to the equipment at Greenwich in 1721, replacing the huge quadrant previously used. The development and perfection of the chronometer in the next hundred years added to the accuracy of observations.

Other national observatories were constructed in the years that followed: at Berlin in 1705, St. Petersburg in 1725, Palermo in 1790, Cape of Good Hope in 1820, Parramatta in New South Wales in 1822, and Sydney in 1855.

123. The International Hydrographic Organization

The **International Hydrographic Organization (IHO)** was originally established in 1921 as the International Hydrographic Bureau (IHB). The present name was adopted in 1970 as a result of a revised international agreement among member nations. However, the former name, International Hydrographic Bureau, was retained for the IHO's administrative body of three Directors and a small staff at the organization's headquarters in Monaco.

The IHO sets forth hydrographic standards to be agreed upon by the member nations. All member states are urged and encouraged to follow these standards in their surveys, nautical charts, and publications. As these standards are uniformly adopted, the products of the world's hydrographic and oceanographic offices become more uniform. Much has been done in the field of standardization since the

Bureau was founded.

The principal work undertaken by the IHO is:

- To bring about a close and permanent association between national hydrographic offices.
- To study matters relating to hydrography and allied sciences and techniques.
- To further the exchange of nautical charts and documents between hydrographic offices of member governments.
- To circulate the appropriate documents.
- To tender guidance and advice upon request, in particular to countries engaged in setting up or expanding their hydrographic service.
- To encourage coordination of hydrographic surveys with relevant oceanographic activities.
- To extend and facilitate the application of oceanographic knowledge for the benefit of navigators.
- To cooperate with international organizations and scientific institutions which have related objectives.

During the 19th century, many maritime nations established hydrographic offices to provide means for improving the navigation of naval and merchant vessels by providing nautical publications, nautical charts, and other navigational services. There were substantial differences in hydrographic procedures, charts, and publications. In 1889, an International Marine Conference was held at Washington, D. C., and it was proposed to establish a "permanent international commission." Similar proposals were made at the sessions of the International Congress of Navigation held at St. Petersburg in 1908 and again in 1912.

In 1919 the hydrographers of Great Britain and France cooperated in taking the necessary steps to convene an international conference of hydrographers. London was selected as the most suitable place for this conference, and on July 24, 1919, the First International Conference opened, attended by the hydrographers of 24 nations. The object of the conference was "To consider the advisability of all maritime nations adopting similar methods in the preparation, construction, and production of their charts and all hydrographic publications; of rendering the results in the most convenient form to enable them to be readily used; of instituting a prompt system of mutual exchange of hydrographic information between all countries; and of providing an opportunity to consultations and discussions to be carried out on hydrographic subjects generally by the hydrographic experts of the world." This is still the major purpose of the International Hydrographic Organization.

As a result of the conference, a permanent organization was formed and statutes for its operations were prepared. The International Hydrographic Bureau, now the International Hydrographic Organization, began its activities in 1921 with 18 nations as members. The Principality of Monaco was selected because of its easy communication with the rest of the world and also because of the generous offer of Prince Albert I of Monaco to provide suitable accommodations for the Bureau in the Principality. There are currently 59 member governments. Technical assistance with hydrographic matters is available through the IHO to member states requiring it.

Many IHO publications are available to the general public, such as the International Hydrographic Review, International Hydrographic Bulletin, Chart Specifications of the IHO, Hydrographic Dictionary, and others. Inquiries should be made to the International Hydrographic Bureau, 7 Avenue President J. F. Kennedy, B.P. 445, MC98011, Monaco, CEDEX.

124. The International Maritime Organization

The **International Maritime Organization (IMO)** was established by United Nations Convention in 1948. The Convention actually entered into force in 1959, although an international convention on marine pollution was adopted in 1954. (Until 1982 the official name of the organization was the Inter-Governmental Maritime Consultative Organization.) It is the only permanent body of the U. N. devoted to maritime matters, and the only special U. N. agency to have its headquarters in the UK.

The governing body of the IMO is the **Assembly** of 137 member states, which meets every two years. Between Assembly sessions a Council, consisting of 32 member governments elected by the Assembly, governs the organization. Its work is carried out by the following committees:

- Maritime Safety Committee, with subcommittees for:
- Safety of Navigation
- Radiocommunications
- Life-saving
- Search and Rescue
- Training and Watchkeeping
- Carriage of Dangerous Goods
- Ship Design and Equipment
- Fire Protection
- Stability and Load Lines/Fishing Vessel Safety
- Containers and Cargoes
- Bulk Chemicals
- Marine Environment Protection Committee
- Legal Committee
- Technical Cooperation Committee
- Facilitation Committee

IMO is headed by the Secretary General, appointed by the council and approved by the Assembly. He is assisted by some 300 civil servants.

To achieve its objectives of coordinating international policy on marine matters, the IMO has adopted some 30 conventions and protocols, and adopted over 700 codes and recommendations. An issue to be adopted first is brought before a committee or subcommittee, which submits a draft to a conference. When the conference adopts the final text, it is submitted

to member governments for ratification. Ratification by a specified number of countries is necessary for adoption; the more important the issue, the more countries must ratify. Adopted conventions are binding on member governments.

Codes and recommendations are not binding, but in most cases are supported by domestic legislation by the governments involved.

The first and most far-reaching convention adopted by the IMO was the Convention of **Safety of Life at Sea (SOLAS)** in 1960. This convention actually came into force in 1965, replacing a version first adopted in 1948. Because of the difficult process of bringing amendments into force internationally, none of subsequent amendments became binding. To remedy this situation, a new convention was adopted in 1974, and became binding in 1980. Among the regulations is V-20, requiring the carriage of up-to-date charts and publications sufficient for the intended voyage.

Other conventions and amendments were also adopted, such as the International Convention on Load Lines (adopted 1966, came into force 1968), a convention on the tonnage measurement of ships (adopted 1969, came into force 1982), The International Convention on Safe Containers (adopted 1972, came into force 1977), and the convention on **International Regulations for Preventing Collisions at Sea (COLREGS)** (adopted 1972, came into force 1977).

The 1972 COLREGS convention contained, among other provisions, a section devoted to Traffic Separation Schemes, which became binding on member states after having been adopted as recommendations in prior years.

One of the most important conventions is the **International Convention for the Prevention of Pollution from Ships (MARPOL 73/78)**, which was first adopted in 1973, amended by Protocol in 1978, and became binding in 1983. This convention built on a series of prior conventions and agreements dating from 1954, highlighted by several severe pollution disasters involving oil tankers. The MARPOL convention reduces the amount of oil discharged into the sea by ships, and bans discharges completely in certain areas. A related convention known as the London Dumping Convention regulates dumping of hazardous chemicals and other debris into the sea.

IMO also develops minimum performance standards for a wide range of equipment relevant to safety at sea. Among such standards is one for the **Electronic Chart Display and Information System (ECDIS)**, the digital display deemed the operational and legal equivalent of the conventional paper chart.

Texts of the various conventions and recommendations, as well as a catalog and publications on other subjects, are available from the Publications Section of the IMO at 4 Albert Embankment, London SE1 7SR, United Kingdom.

125. The International Association Of Lighthouse Authorities

The **International Association of Lighthouse Authorities (IALA)** brings together representatives of the aids to navigation services of more than 80 member countries for technical coordination, information sharing, and coordination of improvements to visual aids to navigation throughout the world. It was established in 1957 to provide a permanent organization to support the goals of the Technical Lighthouse Conferences, which had been convening since 1929. The General Assembly of IALA meets about every 4 years. The Council of 20 members meets twice a year to oversee the ongoing programs.

Five technical committees maintain the permanent programs:

- The Marine Marking Committee
- The Radionavigation Systems Committee
- The Vessel Traffic Services (VTS) Committee
- The Reliability Committee
- The Documentation Committee

IALA committees provide important documentation to the IHO and other international organizations, while the IALA Secretariat acts as a clearing house for the exchange of technical information, and organizes seminars and technical support for developing countries.

Its principle work since 1973 has been the implementation of the IALA Maritime Buoyage System, described in Chapter 5, Visual Aids to Navigation. This system replaced some 30 dissimilar buoyage systems in use throughout the world with 2 major systems.

IALA is based near Paris, France in Saint-Germaine-en-Laye.

126. The Radio Technical Commission for Maritime Services

The **Radio Technical Commission for Maritime Services** is a non-profit organization which serves as a focal point for the exchange of information and the development of recommendations and standards related to all aspects of maritime telecommunications.

Specifically, RTCM:

- Promotes ideas and exchanges information on maritime telecommunications.
- Facilitates the development and exchange of views among government, business, and the public.
- Conducts studies and prepares reports on maritime telecommunications issues to improve efficiency and capabilities.
- Suggests minimum essential rules and regulations for effective telecommunications.
- Makes recommendations on important issues.
- Pursues other activities as permitted by its by-laws and membership.

Both government and non-government organizations are members, including many from foreign nations. The or-

ganization consists of a Board of Directors, the Assembly consisting of all Members, Officers, staff, technical advisors, and standing and special committees.

Working committees are formed as needed to develop official RTCM recommendations regarding technical standards and policies in the maritime field. Currently committees exist for maritime safety information, electronic charts, emergency position-indicating radiobeacons (EPIRB's) and personal locator beacons, survival craft telecommunications, differential GPS, and GLONASS. Ad hoc committees address short-term concerns such as regulatory proposals.

RTCM headquarters is in Washington D.C.

127. The National Marine Electronic Association

The **National Marine Electronic Association (NMEA)** is a professional trade association founded in 1957 whose purpose is to coordinate the efforts of marine electronics manufacturers, technicians, government agencies, ship and boat builders, and other interested groups. In addition to certifying marine electronics technicians and professionally recognizing outstanding achievements by corporate and individual members, the NMEA sets standards for the exchange of digital data by all manufacturers of marine electronic equipment. This allows the configuration of integrated navigation system using equipment from different manufacturers.

NMEA works closely with RTCM and other private organizations and with government agencies to monitor the status of laws and regulations affecting the marine electronics industry.

It also sponsors conferences and seminars, and publishes a number of guides and periodicals for members and the general public.

CHAPTER 2

GEODESY AND DATUMS IN NAVIGATION

GEODESY, THE BASIS OF CARTOGRAPHY

200. Definition

Geodesy is the science concerned with the exact positioning of points on the surface of the earth. It also involves the study of variations of the earth's gravity, the application of these variations to exact measurements on the earth, and the study of the exact size and shape of the earth. These factors were unimportant to early navigators because of the relative inaccuracy of their methods. The precise accuracies of today's navigation systems and the global nature of satellite and other long-range positioning methods demand a more complete understanding of geodesy than has ever before been required.

201. The Shape Of The Earth

The irregular **topographic surface** is that upon which actual geodetic measurements are made. The measurements, however, are reduced to the **geoid**. Marine navigation measurements are made on the ocean surface which approximates the geoid.

The **geoid** is a surface along which gravity is always equal and to which the direction of gravity is always perpendicular. The latter is particularly significant because optical instruments containing level devices are commonly used to make geodetic measurements. When properly adjusted, the vertical axis of the instrument coincides with the direction of gravity and is, therefore, perpendicular to the geoid.

The geoid is that surface to which the oceans would conform over the entire earth if free to adjust to the combined effect of the earth's mass attraction and the centrifugal force of the earth's rotation. The ideal ocean surface would be free of ocean currents and salinity changes. Uneven distribution of the earth's mass makes the geoidal surface irregular.

The geoid refers to the actual size and shape of the earth, but such an irregular surface has serious limitations as a mathematical earth model because:

- It has no complete mathematical expression.
- Small variations in surface shape over time introduce small errors in measurement.
- The irregularity of the surface would necessitate a prohibitive amount of computations.

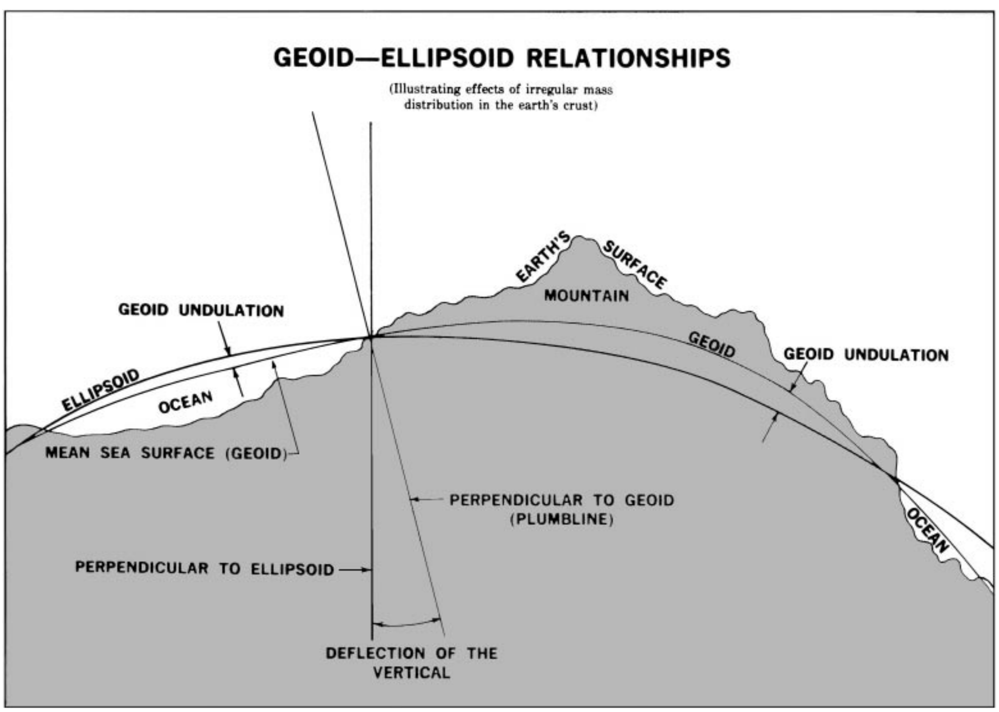


Figure 201. Geiod, ellipsoid, and topographic surface of the earth, and deflection of the vertical due to differences in mass.

The surface of the geoid, with some exceptions, tends to rise under mountains and to dip above ocean basins.

For geodetic, mapping, and charting purposes, it is necessary to use a regular or geometric shape which closely approximates the shape of the geoid either on a local or global scale and which has a specific mathematical expression. This shape is called the **ellipsoid**.

The separations of the geoid and ellipsoid are called **geoidal heights**, **geoidal undulations**, or **geoidal separations**.

The irregularities in density and depths of the material making up the upper crust of the earth also result in slight alterations of the direction of gravity. These alterations are reflected in the irregular shape of the geoid, the surface that is perpendicular to a plumb line.

Since the earth is in fact flattened slightly at the poles and bulges somewhat at the equator, the geometric figure used in geodesy to most nearly approximate the shape of the earth is the **oblate spheroid** or **ellipsoid of revolution**. This is the three dimensional shape obtained by rotating an ellipse about its minor axis.

202. Defining The Ellipsoid

An ellipsoid of revolution is uniquely defined by specifying two parameters. Geodesists, by convention, use the **semimajor axis** and **flattening**. The size is represented by the radius at the equator, the semimajor axis. The shape of the ellipsoid is given by the flattening, which indicates how closely an ellipsoid approaches a spherical shape. The flattening is the ratio of the difference between the semimajor and semiminor axes of the ellipsoid and the semimajor axis. See Figure 202. If a and b represent the semimajor and semiminor axes, respectively, of the ellipsoid, and f is the flattening,

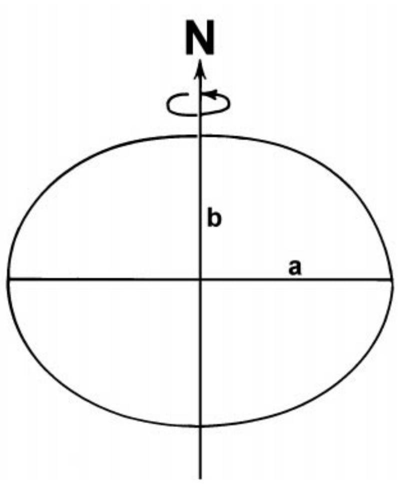


Figure 202. An ellipsoid of revolution, with semimajor axis (a), and semiminor axis (b).

$$f = \frac{a - b}{a}.$$

This ratio is about 1/300 for the earth.
The ellipsoidal earth model has its minor axis parallel to the earth's polar axis.

203. Ellipsoids And The Geoid As Reference Surfaces

Since the surface of the geoid is irregular and the surface of the ellipsoid is regular, no one ellipsoid can provide other than an approximation of part of the geoidal surface. Figure 203 illustrates an example. The ellipsoid that fits well in North America does not fit well in Europe; therefore, it must be positioned differently.

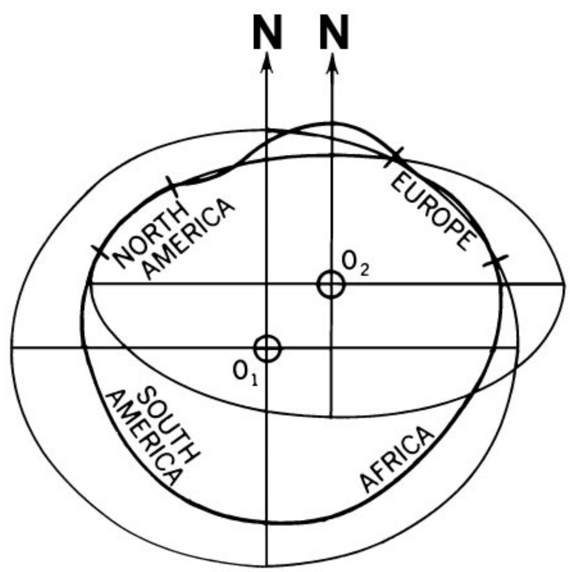


Figure 203. The geoid and two ellipsoids, illustrating how the ellipsoid which fits well in North America will not fit well in Europe, and must have a different origin. (exaggerated for clarity)

A number of reference ellipsoids are used in geodesy and mapping because an ellipsoid is mathematically simpler than the geoid.

204. Coordinates

The **astronomic latitude** is the angle between the plumb line at a station and the plane of the celestial equator. It is the latitude which results directly from observations of celestial bodies, uncorrected for deflection of the vertical component in the meridian (north-south) direction. Astronomic latitude applies only to positions on the earth. It is

reckoned from the astronomic equator (0°), north and south through 90°.

The **astronomic longitude** is the angle between the plane of the celestial meridian at a station and the plane of the celestial meridian at Greenwich. It is the longitude which results directly from observations of celestial bodies, uncorrected for deflection of the vertical component in the prime vertical (east-west) direction. These are the coordinates observed by the celestial navigator using a sextant and a very accurate clock based on the earth's rotation.

Astronomic observations by geodesists are made with optical instruments (theodolite, zenith camera, prismatic astrolabe) which all contain leveling devices. When properly adjusted, the vertical axis of the instrument coincides with the direction of gravity, and is, therefore, perpendicular to the geoid. Thus, astronomic positions are referenced to the geoid. Since the geoid is an irregular, non-mathematical surface, astronomic positions are wholly independent of each other.

The **geodetic latitude** is the angle which the normal to the ellipsoid at a station makes with the plane of the geodetic equator. In recording a geodetic position, it is essential that the geodetic datum on which it is based be also stated. A geodetic latitude differs from the corresponding astronomic latitude by the amount of the meridian component of the local deflection of the vertical.

The **geodetic longitude** is the angle between the plane of the geodetic meridian at a station and the plane of the geodetic meridian at Greenwich. A geodetic longitude differs from the corresponding astronomic longitude by the prime vertical component of the local deflection of the vertical divided by the cosine of the latitude. The geodetic coordinates are used for mapping.

The **geocentric latitude** is the angle at the center of the ellipsoid (used to represent the earth) between the plane of the equator, and a straight line (or radius vector) to a point on the surface of the ellipsoid. This differs from geodetic latitude because the earth is approximated more closely by a spheroid than a sphere and the meridians are ellipses, not perfect circles.

Both geocentric and geodetic latitudes refer to the reference ellipsoid and not the earth. Since the parallels of latitude are considered to be circles, geodetic longitude is geocentric, and a separate expression is not used.

Because of the oblate shape of the ellipsoid, the length of a degree of geodetic latitude is not everywhere the same, increasing from about 59.7 nautical miles at the equator to about 60.3 nautical miles at the poles.

A **horizontal geodetic datum** usually consists of the astronomic and geodetic latitude, and astronomic and geodetic longitude of an initial point (origin); an azimuth of a line (direction); the parameters (radius and flattening) of the ellipsoid selected for the computations; and the geoidal separation at the origin. A change in any of these quantities affects every point on the datum.

For this reason, while positions within a given datum are directly and accurately relateable, those from different datums must be transformed to a common datum for consistency.

TYPES OF GEODETIC SURVEY

205. Triangulation

The most common type of geodetic survey is known as **triangulation**. Triangulation consists of the measurement of the angles of a series of triangles. The principle of triangulation is based on plane trigonometry. If the distance along one side of the triangle and the angles at each end are accurately measured, the other two sides and the remaining angle can be computed. In practice, all of the angles of every triangle are measured to provide precise measurements. Also, the latitude and longitude of one end of the measured side along with the length and direction (azimuth) of the side provide sufficient data to compute the latitude and longitude of the other end of the side.

The measured side of the base triangle is called a **baseline**. Measurements are made as carefully and accurately as possible with specially calibrated tapes or wires of Invar, an alloy highly resistant to changes in length resulting from changes in temperature. The tape or wires are checked periodically against standard measures of length.

To establish an arc of triangulation between two widely separated locations, the baseline may be measured and longitude and latitude determined for the initial points at each location. The lines are then connected by a series of adjoining triangles forming quadrilaterals extending from each end. All angles of the triangles are measured repeatedly to reduce errors. With the longitude, latitude, and azimuth of the initial points, similar data is computed for each vertex of the triangles, thereby establishing triangulation stations, or geodetic control stations. The coordinates of each of the stations are defined as geodetic coordinates.

Triangulation is extended over large areas by connecting and extending series of arcs to form a network or triangulation system. The network is adjusted in a manner which reduces the effect of observational errors to a minimum. A denser distribution of geodetic control is achieved in a system by subdividing or filling in with other surveys.

There are four general classes or orders of triangulation. **First-order** (primary) triangulation is the most precise and exact type. The most accurate instruments and rigorous computation methods are used. It is costly and time-consuming, and is usually used to provide the basic framework of control data for an area, and the determination of the figure of the earth. The most accurate first-order surveys furnish control points which can be interrelated with an accuracy ranging from 1 part in 25,000 over short distances to

approximately 1 part in 100,000 for long distances.

Second-order triangulation furnishes points closer together than in the primary network. While second-order surveys may cover quite extensive areas, they are usually tied to a primary system where possible. The procedures are less exacting and the proportional error is 1 part in 10,000.

Third-order triangulation is run between points in a secondary survey. It is used to densify local control nets and position the topographic and hydrographic detail of the area. Triangle error can amount to 1 part in 5,000.

The sole accuracy requirement for **fourth-order** triangulation is that the positions be located without any appreciable error on maps compiled on the basis of the control. Fourth-order control is done primarily as mapping control.

206. Trilateration, Traverse, And Vertical Surveying

Trilateration involves measuring the sides of a chain of triangles or other polygons. From them, the distance and direction from A to B can be computed. Figure 206 shows this process.

Traverse involves measuring distances and the angles between them without triangles for the purpose of computing the distance and direction from A to B. See Figure 206.

Vertical surveying is the process of determining elevations above mean sea-level. In geodetic surveys executed primarily for mapping, geodetic positions are referred to an ellipsoid, and the elevations of the positions are referred to the geoid. However, for satellite geodesy the geoidal heights must be considered to establish the correct height above the geoid.

Precise geodetic **leveling** is used to establish a basic network of vertical control points. From these, the height of other positions in the survey can be determined by supplementary methods. The mean sea-level surface used as a reference (vertical datum) is determined by averaging the hourly water heights for a specified period of time at specified tide gauges.

There are three leveling techniques: **differential**, **trigonometric**, and **barometric**. Differential leveling is the most accurate of the three methods. With the instrument locked in position, readings are made on two calibrated staffs held in an upright position ahead of and behind the instrument. The difference between readings is the difference in elevation between the points.

Trigonometric leveling involves measuring a vertical angle from a known distance with a theodolite and computing the elevation of the point. With this method, vertical measurement can be made at the same time horizontal angles are measured for triangulation. It is, therefore, a somewhat more economical method but less accurate than differential leveling. It is often the only practical method of establishing accurate elevation control in mountainous areas.

In barometric leveling, differences in height are determined by measuring the differences in atmospheric pressure at various elevations. Air pressure is measured by mercurial or aneroid barometer, or a boiling point thermometer. Although the accuracy of this method is not as great as either of the other two, it obtains relative heights very rapidly at points which are fairly far apart. It is used in reconnaissance and exploratory surveys where more accurate measurements will be made later or where a high degree of accuracy is not required.

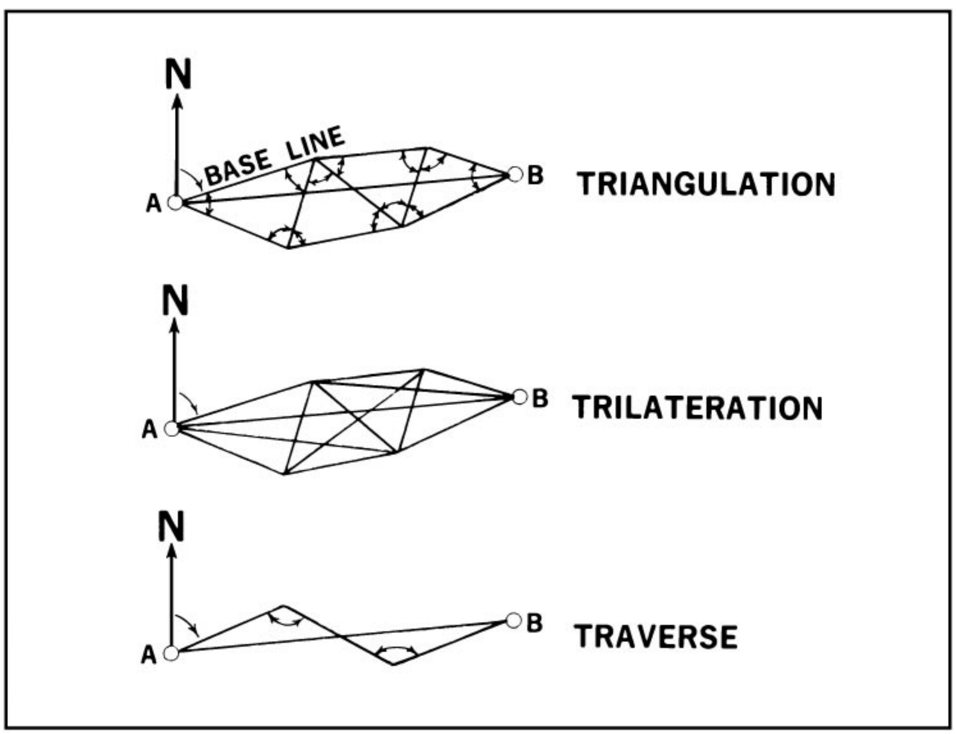


Figure 206. Triangulation, trilateration, and traverse.

DATUM CONNECTIONS

207. Definitions

A **datum** is defined as any numerical or geometrical quantity or set of such quantities which serves as a reference point to measure other quantities.

In geodesy, as well as in cartography and navigation, two types of datums must be considered: a **horizontal datum** and a **vertical datum**. The horizontal datum forms the basis for computations of horizontal position. The vertical datum provides the reference to measure heights. A horizontal datum may be defined at an origin point on the ellipsoid (local datum) such that the center of the ellipsoid coincides with the Earth's center of mass (geocentric datum). The coordinates for points in specific geodetic surveys and triangulation networks are computed from certain initial quantities, or datums.

208. Preferred Datums

In areas of overlapping geodetic triangulation networks, each computed on a different datum, the coordinates of the points given with respect to one datum will differ from those given with respect to the other. The differences can be used to derive transformation formulas. Datums are connected by developing transformation formulas at common points, either between overlapping control networks or by satellite connections.

Many countries have developed national datums which differ from those of their neighbors. Accordingly, national maps and charts often do not agree along national borders.

The **North American Datum, 1927** (NAD 27) has been used in the United States for about 50 years, but it is being replaced by datums based on the **World Geodetic System**. NAD 27 coordinates are based on the latitude and longitude of a triangulation station (the reference point) at Mead's Ranch in Kansas, the azimuth to a nearby triangulation station called Waldo, and the mathematical parameters of the Clarke Ellipsoid of 1866. Other datums throughout the world use different assumptions as to origin points and ellipsoids.

The origin of the **European Datum** is at Potsdam,

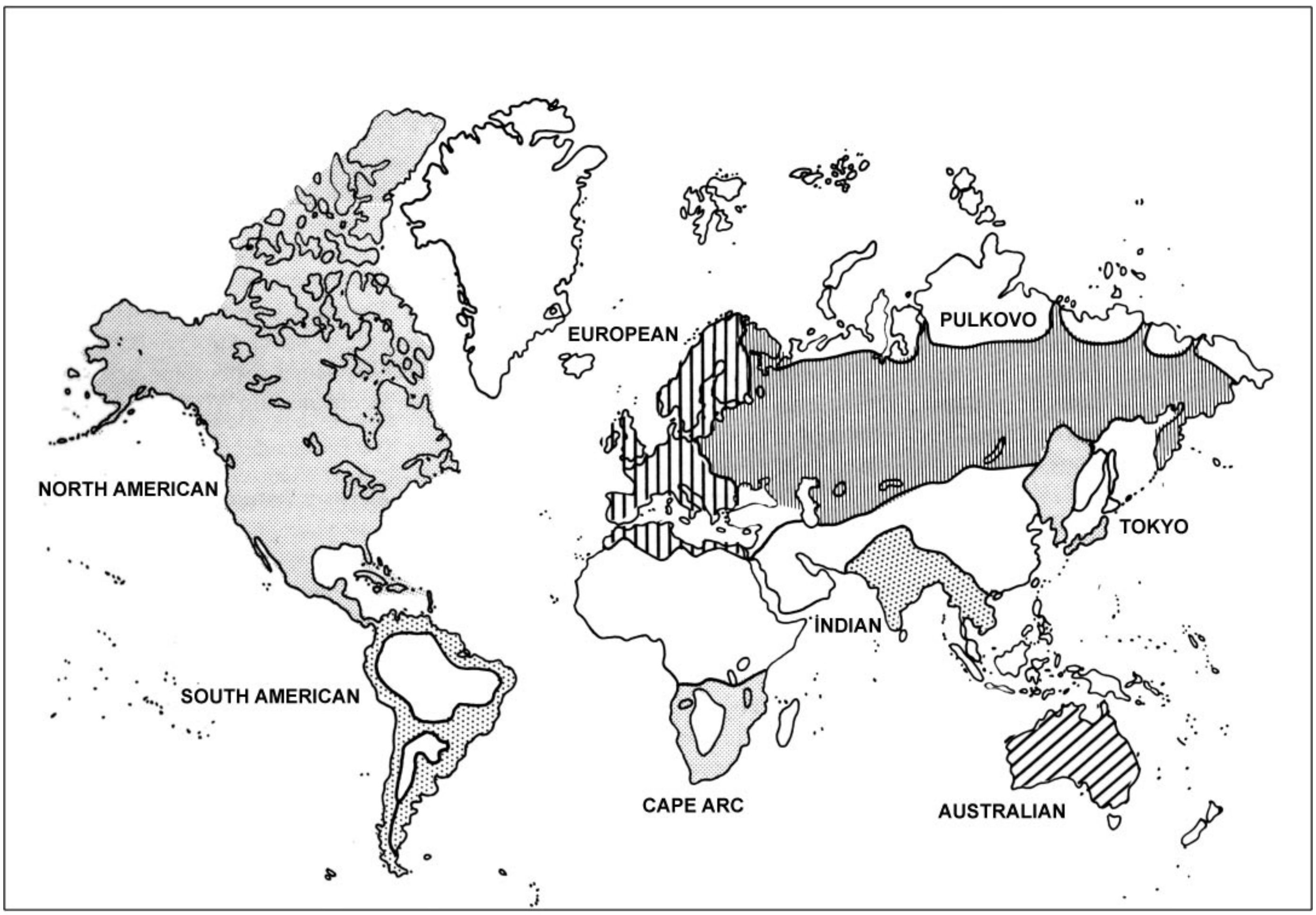


Figure 208. Major geodetic datum blocks.

Germany. Numerous national systems have been joined into a large datum based upon the International Ellipsoid of 1924 which was oriented by a modified astrogeodetic method. European, African, and Asian triangulation chains were connected, and African measurements from Cairo to Cape Town were completed. Thus, all of Europe, Africa, and Asia are molded into one great system. Through common survey stations, it was also possible to convert data from the Russian Pulkova, 1932 system to the European Datum, and as a result, the European Datum includes triangulation as far east as the 84th meridian. Additional ties across the Middle East have permitted connection of the Indian and European Datums.

The **Ordnance Survey of Great Britain 1936 Datum** has no point of origin. The data was derived as a best fit between retriangulation and original values of 11 points of the earlier Principal Triangulation of Great Britain (1783-1853).

Tokyo Datum has its origin in Tokyo. It is defined in terms of the Bessel Ellipsoid and oriented by a single astronomic station. Triangulation ties through Korea connect the Japanese datum with the Manchurian datum. Unfortunately, Tokyo is situated on a steep slope on the geoid, and the single-station orientation has resulted in large systematic geoidal separations as the system is extended from its initial point.

The **Indian Datum** is the preferred datum for India and several adjacent countries in Southeast Asia. It is computed on the Everest Ellipsoid with its origin at Kalianpur, in central India. It is largely the result of the untiring work of Sir George Everest (1790-1866), Surveyor General in India from 1830 to 1843. He is best known by the mountain named after him, but by far his most important legacy was the survey of the Indian subcontinent.

MODERN GEODETIC SYSTEMS

209. Development Of The World Geodetic System

By the late 1950's the increasing range and sophistication of weapons systems had rendered local or national datums inadequate for military purposes; these new weapons required datums at least continental in scope. In response to these requirements, the U.S. Department of Defense generated a geocentric reference system to which different geodetic networks could be referred and established compatibility between the coordinates of sites of interest. Efforts of the Army, Navy, and Air Force were combined leading to the development of the DoD **World Geodetic System of 1960 (WGS 60)**.

In January 1966, a World Geodetic System Committee was charged with the responsibility for developing an improved WGS needed to satisfy mapping, charting, and geodetic requirements. Additional surface gravity observations, results from the extension of triangulation and trilateration networks, and large amounts of Doppler and optical satellite data had become available since the development of WGS 60. Using the additional data and improved techniques, the Committee produced **WGS 66** which served DoD needs following its implementation in 1967.

The same World Geodetic System Committee began work in 1970 to develop a replacement for WGS 66. Since the development of WGS 66, large quantities of additional data had become available from both Doppler and optical satellites, surface gravity surveys, triangulation and trilateration surveys, high precision traverses, and astronomic surveys.

In addition, improved capabilities had been developed in both computers and computer software. Continued research in computational procedures and error analyses had produced better methods and an improved facility for handling and combining data. After an extensive effort extending over a period of approximately three years, the Committee completed the development of the Department of Defense **World Geodetic System 1972 (WGS 72)**.

Further refinement of WGS 72 resulted in the new **World Geodetic System of 1984 (WGS 84)**. As of 1990, WGS 84 is being used for chart making by DMA. For surface navigation, WGS 60, 66, 72 and the new WGS 84 are essentially the same, so that positions computed on any WGS coordinates can be plotted directly on the others without correction.

The WGS system is not based on a single point, but many points, fixed with extreme precision by satellite fixes and statistical methods. The result is an ellipsoid which fits the real surface of the earth, or geoid, far more accurately than any other. The WGS system is applicable worldwide. All regional datums can be referenced to WGS once a survey tie has been made.

210. The New North American Datum Of 1983

The Coast And Geodetic Survey of the National Ocean Service (NOS), NOAA, is responsible for charting United States waters. From 1927 to 1987, U.S. charts were based on NAD 27, using the Clarke 1866 ellipsoid. In 1989, the U.S. officially switched to **NAD 83** (navigationally equivalent to WGS 84 and other WGS systems) for all mapping and charting purposes, and all new NOS chart production is based on this new standard.

The grid of interconnected surveys which criss-crosses the United States consists of some 250,000 control points, each consisting of the latitude and longitude of the point, plus additional data such as elevation. Converting the NAD 27 coordinates to NAD 83 involved recomputing the position of each point based on the new NAD 83 datum. In addition to the 250,000 U.S. control points, several thousand more were added to tie in surveys from Canada, Mexico, and Central America.

Conversion of new edition charts to the new datums, either WGS 84 or NAD 83, involves converting reference

points on each chart from the old datum to the new, and adjusting the latitude and longitude grid (known as the graticule) so that it reflects the newly plotted positions. This adjustment of the graticule is the only difference between charts which differ only in datum. All charted features remain in exactly the same relative positions.

IMPACTS ON NAVIGATION

211. Datum Shifts

One impact of different datums on navigation appears when a navigation system provides a fix based on a datum different from that used for the nautical chart. The resulting plotted position may be different from the actual location on that chart. This difference is known as a **datum shift**.

Another effect on navigation occurs when shifting between charts that have been made using different datums. If any position is replotted on a chart of another datum using only latitude and longitude for locating that position, the newly plotted position will not match with respect to other charted features. This datum shift may be avoided by replotting using bearings and ranges to common points. If datum shift conversion notes for the applicable datums are given on the charts, positions defined by latitude and longitude may be replotted after applying the noted correction.

The positions given for chart corrections in the Notice to Mariners reflect the proper datum for each specific chart and edition number. Due to conversion of charts based on old datums to more modern ones, and the use of many different datums throughout the world, chart corrections intended for one edition of a chart may not be safely plotted on any other.

These datum shifts are not constant throughout a given area, but vary according to how the differing datums fit together. For example, the NAD 27 to NAD 83 conversion results in changes in latitude of 40 meters in Miami, 11 meters in New York, and 20 meters in Seattle. Longitude changes for this conversion are about 22 meters in Miami, 35 meters in New York, and 93 meters in Seattle.

Most charts produced by DMA and NOS show a “datum note.” This note is usually found in the title block or in the upper left margin of the chart. According to the year of the chart edition, the scale, and policy at the time of production, the note may say “World Geodetic System 1972 (WGS-72)”, “World Geodetic System 1984 (WGS-84)”, or “World Geodetic System (WGS).” A datum note for a chart for which satellite positions can be plotted without correction will read: “Positions obtained from satellite navigation systems referred to (REFERENCE DATUM) can be plotted directly on this chart.”

DMA reproductions of foreign chart‘s will usually be in the datum or reference system of the producing country. In these cases a conversion factor is given in the following format: “Positions obtained from satellite navigation systems referred to the (Reference Datum) must be moved X.XX minutes (Northward/Southward) and X.XX minutes (Eastward/ Westward) to agree with this chart.”

Some charts cannot be tied in to WGS because of lack of recent surveys. Currently issued charts of some areas are based on surveys or use data obtained in the age of sailing ships. The lack of surveyed control points means that they cannot be properly referenced to modern geodetic systems. In this case there may be a note that says: “Adjustments to WGS cannot be determined for this chart.”

A few charts may have no datum note at all, but may carry a note which says: “From various sources to (year).” In these cases there is no way for the navigator to determine the mathematical difference between the local datum and WGS positions. However, if a radar or visual fix can be very accurately determined, the difference between this fix and a satellite fix can determine an approximate correction factor which will be reasonably consistent for that local area.

212. Minimizing Errors Caused By Differing Datums

To minimize problems caused by differing datums:

- Plot chart corrections only on the specific charts and editions for which they are intended. Each chart correction is specific to only one edition of a chart. When the same correction is made on two charts based on different datums, the positions for the same feature may differ slightly. This difference is equal to the datum shift between the two datums for that area.
- Try to determine the source and datum of positions of temporary features, such as drill rigs. In general they are given in the datum used in the area in question. Since these are usually positioned using satellites, WGS is the normal datum. A datum correction, if needed, might be found on a chart of the area.
- Remember that if the datum of a plotted feature is not known, position inaccuracies may result. It is wise to allow a margin of error if there is any doubt about the datum.
- Know how the datum of the positioning system you are using (Loran, GPS, etc.) relates to your chart. GPS and other modern positioning systems use the WGS datum. If your chart is on any other datum, you must apply a datum correction when plotting the GPS position of the chart.

Modern geodesy can support the goal of producing all the world’s charts on the same datum. Coupling an electronic chart with satellite positioning will eliminate the problem of differing datums because electronically derived positions and the video charts on which they are displayed are derived from one of the new worldwide datums.

CHAPTER 3

NAUTICAL CHARTS

CHART FUNDAMENTALS

300. Definitions

A **nautical chart** represents part of the spherical earth on a plane surface. It shows water depth, the shoreline of adjacent land, topographic features, aids to navigation, and other navigational information. It is a work area on which the navigator plots courses, ascertains positions, and views the relationship of the ship to the surrounding area. It assists the navigator in avoiding dangers and arriving safely at his destination.

The actual form of a chart may vary. Traditional nautical charts have been printed on paper. **Electronic charts** consisting of a digital data base and a display system are in use and will eventually replace paper charts for operational use. An electronic chart is not simply a digital version of a paper chart; it introduces a new navigation methodology with capabilities and limitations very different from paper charts. The electronic chart will eventually become the legal equivalent of the paper chart when approved by the International Maritime Organization and the various governmental agencies which regulate navigation. Currently, however, mariners must maintain a paper chart on the bridge. See Chapter 14, The Integrated Bridge, for a discussion of electronic charts.

Should a marine accident occur, the nautical chart in use at the time takes on legal significance. In cases of grounding, collision, and other accidents, charts become critical records for reconstructing the event and assigning liability. Charts used in reconstructing the incident can also have tremendous training value.

301. Projections

Because a cartographer cannot transfer a sphere to a flat surface without distortion, he must project the surface of a sphere onto a **developable surface**. A developable surface is one that can be flattened to form a plane. This process is known as **chart projection**. If points on the surface of the sphere are projected from a single point, the projection is said to be **perspective** or **geometric**.

As the use of electronic charts becomes increasingly widespread, it is important to remember that the same cartographic principles that apply to paper charts apply to their depiction on video screens.

302. Selecting A Projection

Each projection has certain preferable features. However, as the area covered by the chart becomes smaller, the differences between various projections become less noticeable. On the largest scale chart, such as of a harbor, all projections are practically identical. Some desirable properties of a projection are:

1. True shape of physical features.
2. Correct angular relationship. A projection with this characteristic is **conformal** or **orthomorphic**.
3. Equal area, or the representation of areas in their correct relative proportions.
4. Constant scale values for measuring distances.
5. Great circles represented as straight lines.
6. Rhumb lines represented as straight lines.

Some of these properties are mutually exclusive. For example, a single projection cannot be both conformal and equal area. Similarly, both great circles and rhumb lines cannot be represented on a single projection as straight lines.

303. Types Of Projections

The type of developable surface to which the spherical surface is transferred determines the projection's classification. Further classification depends on whether the projection is centered on the equator (equatorial), a pole (polar), or some point or line between (oblique). The name of a projection indicates its type and its principal features.

Mariners most frequently use a **Mercator projection**, classified as a **cylindrical projection** upon a plane, the cylinder tangent along the equator. Similarly, a projection based upon a cylinder tangent along a meridian is called **transverse** (or inverse) **Mercator** or **transverse** (or inverse) **orthomorphic**. The Mercator is the most common projection used in maritime navigation, primarily because rhumb lines plot as straight lines.

In a **simple conic projection**, points on the surface of the earth are transferred to a tangent cone. In the **Lambert conformal projection**, the cone intersects the earth (a secant cone) at two small circles. In a **polyconic projection**, a series of tangent cones is used.

In an **azimuthal** or **zenithal projection**, points on the earth are transferred directly to a plane. If the origin of the projecting rays is the center of the earth, a **gnomonic projection** results; if it is the point opposite the plane's point of tangency, a **stereographic projection**; and if at infinity (the projecting lines being parallel to each other), an **orthographic projection**. The gnomonic, stereographic, and orthographic are **perspective projections**. In an **azimuthal equidistant projection**, which is not perspective, the scale of distances is constant along any radial line from the point of tangency. See Figure 303.

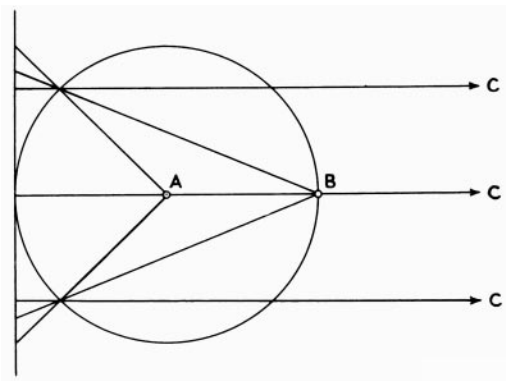


Figure 303. Azimuthal projections: A, gnomonic; B, stereographic; C, (at infinity) orthographic.

Cylindrical and **plane projections** are special conical projections, using heights infinity and zero, respectively.

A **graticule** is the network of latitude and longitude lines laid out in accordance with the principles of any projection.

304. Cylindrical Projections

If a cylinder is placed around the earth, tangent along the equator, and the planes of the meridians are extended, they intersect the cylinder in a number of vertical lines. See Figure 304. These parallel lines of projection are equidistant from each other, unlike the terrestrial meridians from which they are derived which converge as the latitude increases. On the earth, parallels of latitude are perpendicular to the meridians, forming circles of progressively smaller diameter as the latitude increases. On the cylinder they are shown perpendicular to the projected meridians, but because a cylinder is everywhere of the same diameter, the projected parallels are all the same size.

If the cylinder is cut along a vertical line (a meridian) and spread out flat, the meridians appear as equally spaced vertical lines; and the parallels appear as horizontal lines. The parallels' relative spacing differs in the various types of cylindrical projections.

If the cylinder is tangent along some great circle other than the equator, the projected pattern of latitude and longitude lines appears quite different from that described above, since the line of tangency and the equator no longer coincide. These projections are classified as **oblique** or **transverse projections**.

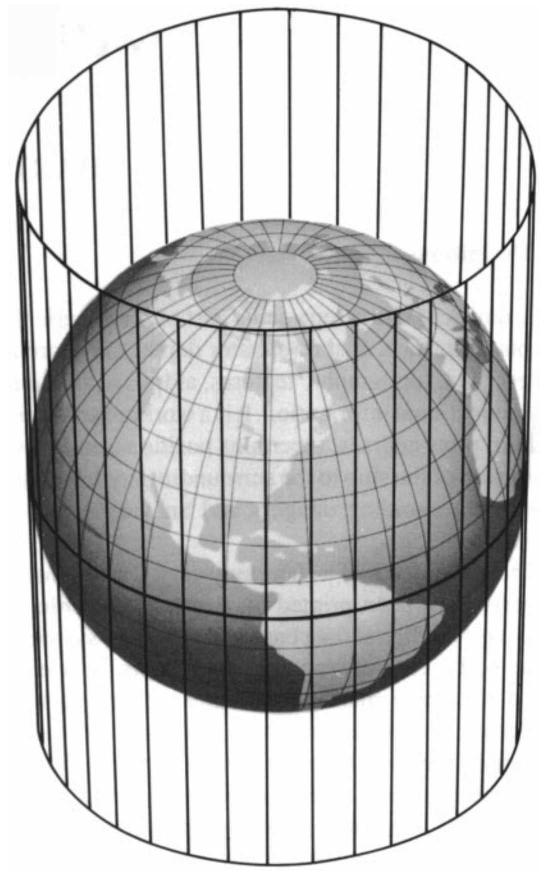


Figure 304. A cylindrical projection.

305. Mercator Projection

Navigators most often use the plane conformal projection known as the **Mercator projection**. The Mercator projection is not perspective, and its parallels can be derived mathematically as well as projected geometrically. Its distinguishing feature is that both the meridians and parallels are expanded at the same ratio with increased latitude. The expansion is equal to the secant of the latitude, with a small correction for the ellipticity of the earth. Since the secant of 90° is infinity, the projection cannot include the poles. Since the projection is conformal, expansion is the same in all directions and angles are correctly shown. Rhumb lines appear as straight lines, the directions of which can be measured directly on the chart. Distances can also be measured directly if the spread of latitude is small. Great circles, except meridians and the equator, appear as curved lines concave to the equator. Small areas appear in their correct shape but of increased size unless they are near the equator.

306. Meridional Parts

At the equator a degree of longitude is approximately

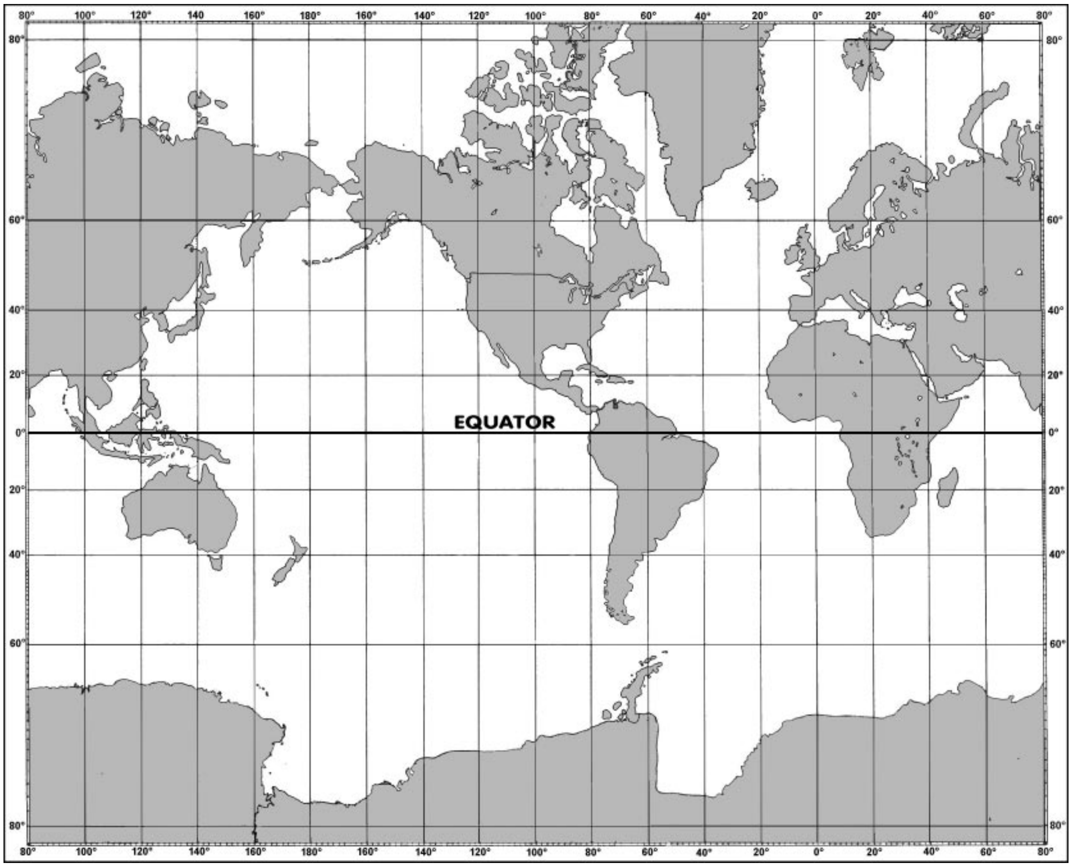


Figure 306. A Mercator map of the world.

equal in length to a degree of latitude. As the distance from the equator increases, degrees of latitude remain approximately the same, while degrees of longitude become progressively shorter. Since degrees of longitude appear everywhere the same length in the Mercator projection, it is necessary to increase the length of the meridians if the expansion is to be equal in all directions. Thus, to maintain the correct proportions between degrees of latitude and degrees of longitude, the degrees of latitude must be progressively longer as the distance from the equator increases. This is illustrated in Figure 306.

The length of a meridian, increased between the equator and any given latitude, expressed in minutes of arc at the equator as a unit, constitutes the number of meridional parts (M) corresponding to that latitude. Meridional parts, given in Table 6 for every minute of latitude from the equator to the pole, make it possible to construct a Mercator chart and to solve problems in Mercator sailing. These values are for the WGS ellipsoid of 1984.

307. Transverse Mercator Projections

Constructing a chart using Mercator principles, but with the cylinder tangent along a meridian, results in a **transverse Mercator** or **transverse orthomorphic projection**. The word "inverse" is used interchangeably with "transverse." These projections use a fictitious graticule similar to, but offset from, the familiar network of meridians and parallels. The tangent great circle is the fictitious equator. Ninety degrees from it are two fictitious poles. A group of great circles through these poles and perpendicular to the tangent great circle are the fictitious meridians, while a series of circles parallel to the plane of the tangent great circle form the fictitious parallels. The actual meridians and parallels appear as curved lines.

A straight line on the transverse or oblique Mercator projection makes the same angle with all fictitious meridians, but not with the terrestrial meridians. It is therefore a fictitious rhumb line. Near the tangent great circle, a straight line closely approximates a great circle. The projection is most useful in this area. Since the area of minimum distortion is near a meridian, this projection is useful for charts covering a large band of latitude and extending a relatively short distance on each side of the tangent meridian. It is sometimes used for star charts showing the evening sky at various seasons of the year. See Figure 307.

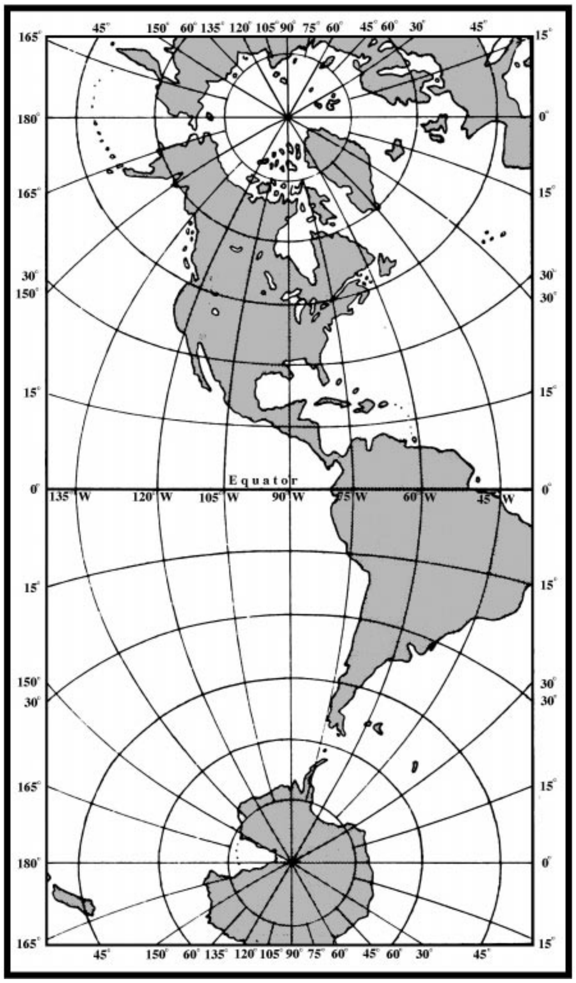


Figure 307. A transverse Mercator map of the Western Hemisphere.

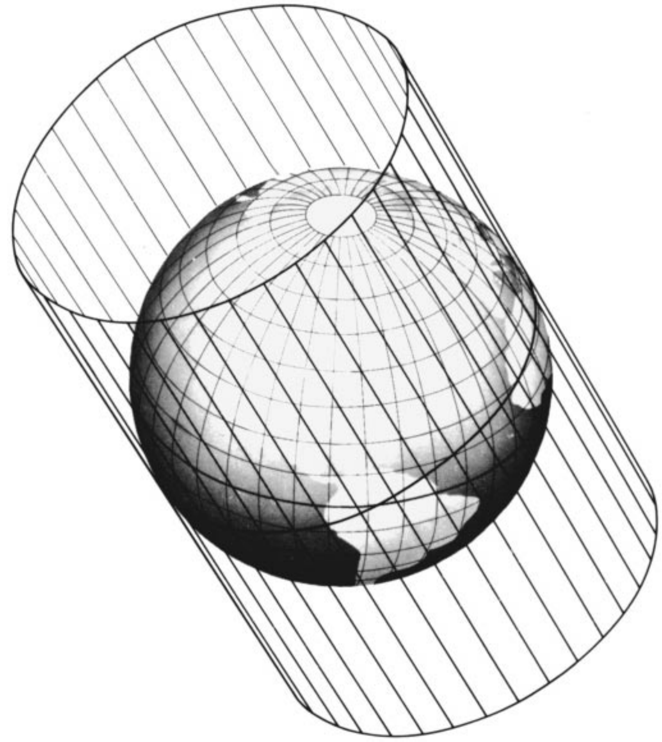


Figure 309a. An oblique Mercator projection.

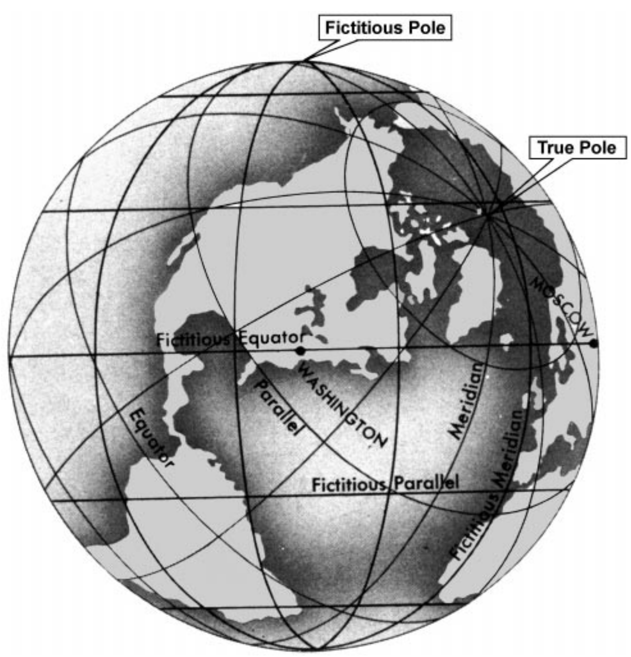


Figure 309b. The fictitious graticle of an oblique Mercator projection.

308. Universal Transverse Mercator (UTM) Grid

The **Universal Transverse Mercator (UTM)** grid is a military grid superimposed upon a transverse Mercator graticule, or the representation of these grid lines upon any graticule. This grid system and these projections are often used for large-scale (harbor) nautical charts and military charts.

309. Oblique Mercator Projections

A Mercator projection in which the cylinder is tangent along a great circle other than the equator or a meridian is called an **oblique Mercator** or **oblique orthomorphic projection**. This projection is used principally to depict an area in the near vicinity of an oblique great circle. Figure 309c, for example, shows the great circle joining Washington and Moscow. Figure 309d shows an oblique Mercator map with the great circle between these two centers as the tangent great circle or fictitious equator. The limits of the chart of Figure 309c are indicated in Figure 309d. Note the large variation in scale as the latitude changes.

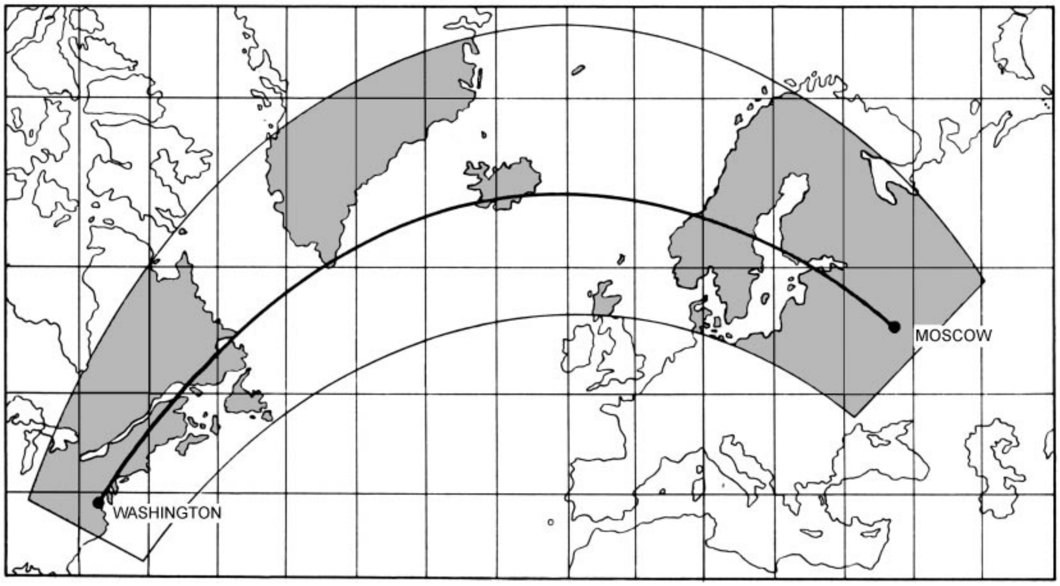


Figure 309c. The great circle between Washington and Moscow as it appears on a Mercator map.

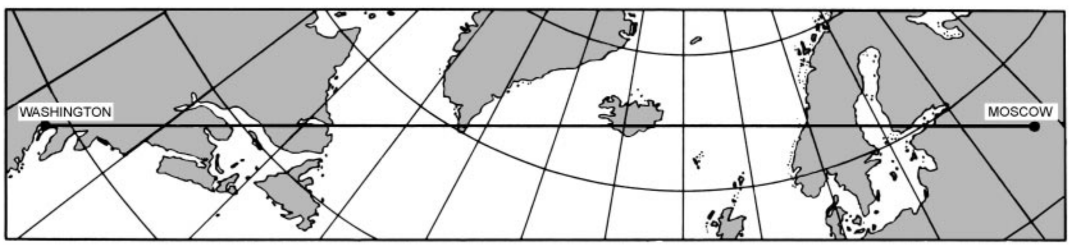


Figure 309d. An oblique Mercator map based upon a cylinder tangent along the great circle through Washington and Moscow. The map includes an area 500 miles on each side of the great circle. The limits of this map are indicated on the Mercator map of Figure 309c.

310. Rectangular Projection

A cylindrical projection similar to the Mercator, but with uniform spacing of the parallels, is called a **rectangular projection**. It is convenient for graphically depicting information where distortion is not important. The principal navigational use of this projection is for the star chart of the Air Almanac, where positions of stars are plotted by rectangular coordinates representing declination (ordinate) and sidereal hour angle (abscissa). Since the meridians are parallel, the parallels of latitude (including the equator and the poles) are all represented by lines of equal length.

311. Conic Projections

A **conic projection** is produced by transferring points from the surface of the earth to a cone or series of cones. This cone is then cut along an element and spread out flat to form the chart. When the axis of the cone coincides with the axis of the earth, then the parallels appear as arcs of circles, and the meridians appear as either straight or curved lines converging toward the nearer pole. Limiting the area covered to that part of the cone near the surface of the earth limits distortion. A parallel along which there is no distortion is called a **standard parallel**. Neither the transverse conic projection, in which the axis of the cone is in the equatorial plane, nor the oblique conic projection, in which the axis of the cone is oblique to the plane of the equator, is ordinarily used for navigation. They are typically used for illustrative maps.

Using cones tangent at various parallels, a secant (intersecting) cone, or a series of cones varies the appearance and features of a conic projection.

312. Simple Conic Projection

A conic projection using a single tangent cone is a **simple conic projection** (Figure 312a). The height of the cone increases as the latitude of the tangent parallel decreases. At the equator, the height reaches infinity and the cone be-

comes a cylinder. At the pole, its height is zero, and the cone becomes a plane. Similar to the Mercator projection, the simple conic projection is not perspective since only the meridians are projected geometrically, each becoming an element of the cone. When this projection is spread out flat to form a map, the meridians appear as straight lines converging at the apex of the cone. The standard parallel, where the cone is tangent to the earth, appears as the arc of a circle with its center at the apex of the cone. The other

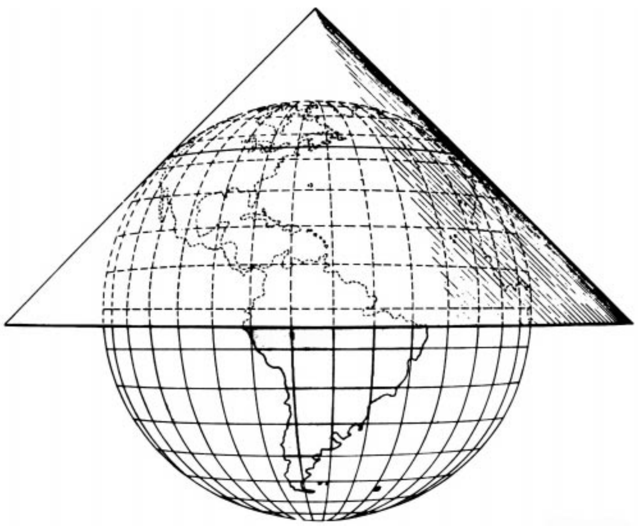


Figure 312a. A simple conic projection.

parallels are concentric circles. The distance along any meridian between consecutive parallels is in correct relation to the distance on the earth, and, therefore, can be derived mathematically. The pole is represented by a circle (Figure 312b). The scale is correct along any meridian and along the standard parallel. All other parallels are too great in length, with the error increasing with increased distance from the standard parallel. Since the scale is not the same in all directions about every point, the projection is neither a conformal nor equal-area projection. Its non-conformal nature is its principal disadvantage for navigation.

Since the scale is correct along the standard parallel and varies uniformly on each side, with comparatively little distortion near the standard parallel, this projection is useful for mapping an area covering a large spread of longitude and a comparatively narrow band of latitude. It was developed by Claudius Ptolemy in the second century A.D. to map just such an area: the Mediterranean Sea.

313. Lambert Conformal Projection

The useful latitude range of the simple conic projection can be increased by using a secant cone intersecting the earth at two standard parallels. See Figure 313. The area between the two standard parallels is compressed, and that beyond is expanded. Such a projection is called either a **secant conic** or **conic projection with two standard parallels**.

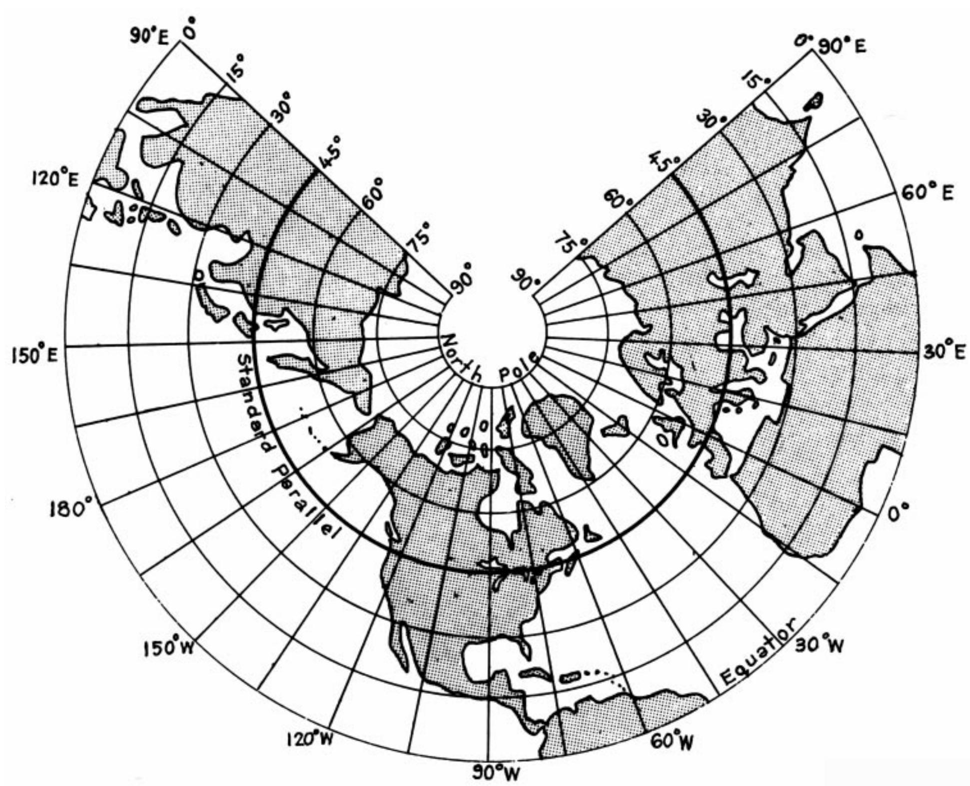


Figure 312b. A simple conic map of the Northern Hemisphere.

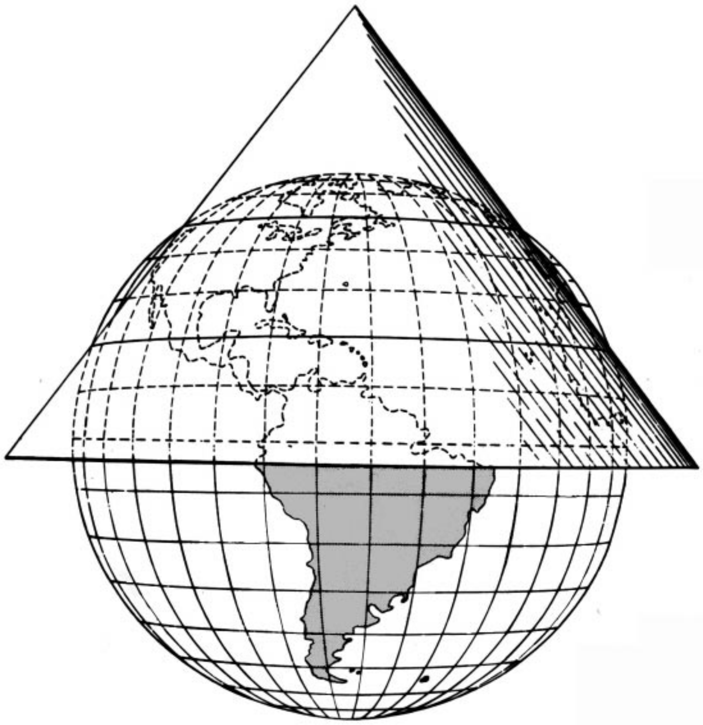


Figure 313. A secant cone for a conic projection with two standard parallels.

If in such a projection the spacing of the parallels is altered, such that the distortion is the same along them as along the meridians, the projection becomes conformal. This modification produces the **Lambert conformal projection**. If the chart is not carried far beyond the standard parallels, and if these are not a great distance apart, the distortion over the entire chart is small.

A straight line on this projection so nearly approximates a great circle that the two are nearly identical. Radio beacon signals travel great circles; thus, they can be plotted on this projection without correction. This feature, gained without sacrificing conformality, has made this projection popular for aeronautical charts because aircraft make wide use of radio aids to navigation. Except in high latitudes, where a slightly modified form of this projection has been used for polar charts, it has not replaced the Mercator projection for marine navigation.

314. Polyconic Projection

The latitude limitations of the secant conic projection can be minimized by using a series of cones. This results in a **polyconic projection**. In this projection, each parallel is the base of a tangent cone . At the edges of the chart, the area between parallels is expanded to eliminate gaps. The scale is correct along any parallel and along the central meridian of the projection. Along other meridians the scale increases with increased difference of longitude from the central meridian. Parallels appear as nonconcentric circles; meridians appear as curved lines converging toward the pole and concave to the central meridian.

The polyconic projection is widely used in atlases, particularly for areas of large range in latitude and reasonably large range in longitude, such as continents. However, since it is not conformal, this projection is not customarily used in navigation.

315. Azimuthal Projections

If points on the earth are projected directly to a plane surface, a map is formed at once, without cutting and flattening, or "developing." This can be considered a special case of a conic projection in which the cone has zero height.

The simplest case of the **azimuthal projection** is one in which the plane is tangent at one of the poles. The meridians are straight lines intersecting at the pole, and the parallels are concentric circles with their common center at the pole. Their spacing depends upon the method used to transfer points from the earth to the plane.

If the plane is tangent at some point other than a pole, straight lines through the point of tangency are great circles, and concentric circles with their common center at the point of tangency connect points of equal distance from that point. Distortion, which is zero at the point of tangency, increases along any great circle through this point. Along any circle whose center is the point of tangency, the distortion is constant. The bearing of any point from the point of tangency is correctly represented. It is for this reason that these projections are called **azimuthal**. They are also called **zenithal**. Several of the common azimuthal projections are perspective.

316. Gnomonic Projection

If a plane is tangent to the earth, and points are projected geometrically from the center of the earth, the result is a **gnomonic projection**. See Figure 316a. Since the projection is perspective, it can be demonstrated by placing a light at the center of a transparent terrestrial globe and holding a

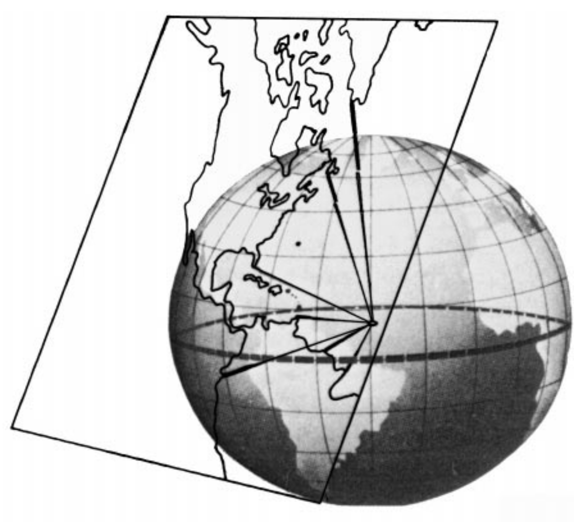


Figure 316a. An oblique gnomonic projection.

flat surface tangent to the sphere.

In an **oblique gnomonic projection** the meridians appear as straight lines converging toward the nearer pole. The parallels, except the equator, appear as curves (Figure 316b). As in all azimuthal projections, bearings from the point of tangency are correctly represented. The distance scale, however, changes rapidly. The projection is neither conformal nor equal area. Distortion is so great that shapes, as well as distances and areas, are very poorly represented, except near the point of tangency.

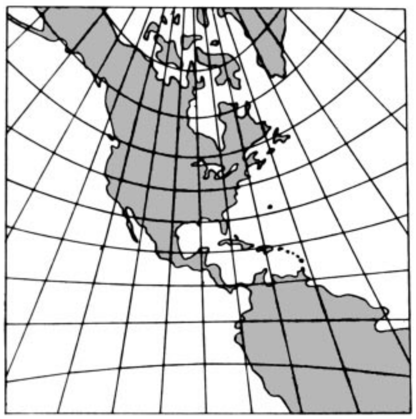


Figure 316b. An oblique gnomonic map with point of tangency at latitude 30°N, longitude 90°W.

The usefulness of this projection rests upon the fact that any great circle appears on the map as a straight line, giving charts made on this projection the common name **great-circle charts**.

Gnomonic charts are most often used for planning the great-circle track between points. Points along the determined track are then transferred to a Mercator projection. The great circle is then followed by following the rhumb lines from one point to the next. Computer programs which automatically calculate great circle routes between points and provide latitude and longitude of corresponding rhumb line endpoints are quickly making this use of the gnomonic chart obsolete.

317. Stereographic Projection

A **stereographic projection** results from projecting points on the surface of the earth onto a tangent plane, from a point on the surface of the earth opposite the point of tangency (Figure 317a). This projection is also called an **azimuthal orthomorphic projection**.

The scale of the stereographic projection increases with distance from the point of tangency, but it increases more slowly than in the gnomonic projection. The stereographic projection can show an entire hemisphere without excessive distortion (Figure 317b). As in other azimuthal projections, great circles through the point of tangency appear as straight lines. Other circles such as meridians and parallels appear as either circles or arcs of circles.

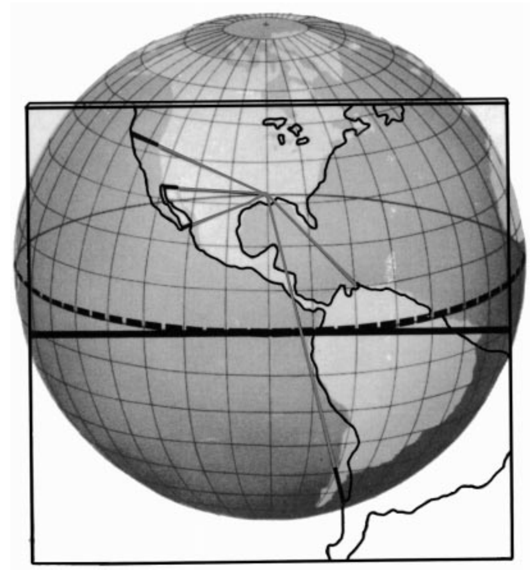


Figure 317a. An equatorial stereographic projection.

Figure 317b. A stereographic map of the Western Hemisphere.

The principal navigational use of the stereographic projection is for charts of the polar regions and devices for mechanical or graphical solution of the navigational triangle. A **Universal Polar Stereographic (UPS)** grid, mathematically adjusted to the graticule, is used as a reference system.

318. Orthographic Projection

If terrestrial points are projected geometrically from infinity to a tangent plane, an **orthographic projection** results (Figure 318a). This projection is not conformal; nor does it result in an equal area representation. Its principal use is in navigational astronomy because it is useful for illustrating and solving the navigational triangle. It is also useful for illustrating celestial coordinates. If the plane is tangent at a point on the equator, the parallels (including the equator) appear as straight lines. The meridians would appear as ellipses, except that the meridian through the point of tangency would appear as a straight line and the one 90° away would appear as a circle (Figure 318b).

319. Azimuthal Equidistant Projection

An **azimuthal equidistant projection** is an azimuthal projection in which the distance scale along any great circle through the point of tangency is constant. If a pole is the point of tangency, the meridians appear as straight radial lines and the parallels as equally spaced concentric circles. If the plane is tangent at some point other than a pole, the concentric circles represent distances from the point of tangency. In this case, meridians and parallels appear as curves.

The projection can be used to portray the entire earth, the point 180° from the point of tangency appearing as the largest of the concentric circles. The projection is not conformal, equal area, or perspective. Near the point of tangency distortion is small, increasing with distance until shapes near the opposite side of the earth are unrecognizable (Figure 319).

The projection is useful because it combines the three features of being azimuthal, having a constant distance scale from the point of tangency, and permitting the entire earth to be shown on one map. Thus, if an important harbor or airport is selected as the point of tangency, the great-circle course, distance, and track from that point to any other point on the earth are quickly and accurately determined. For communication work with the station at the point of tangency, the path of an incoming signal is at once apparent if the direction of arrival has been determined and the direction to train a directional antenna can be determined easily. The projection is also used for polar charts and for the star finder, No. 2102D.

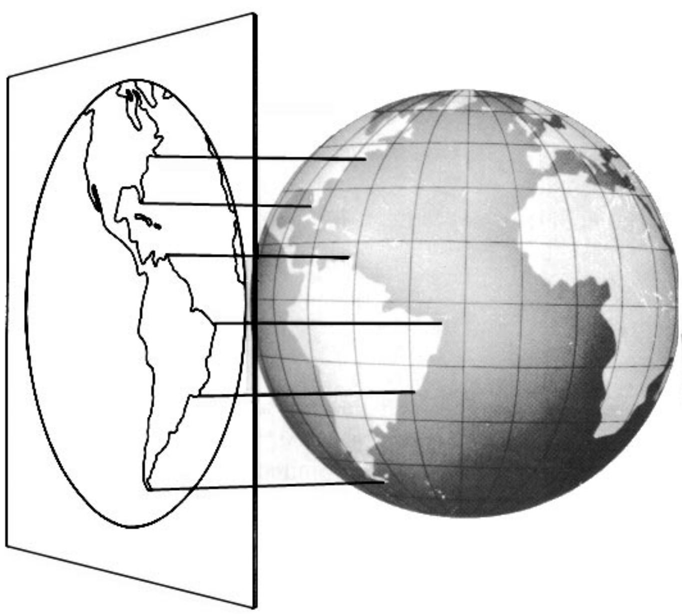


Figure 318a. An equatorial orthographic projection.

Figure 318b. An orthographic map of the Western Hemisphere.

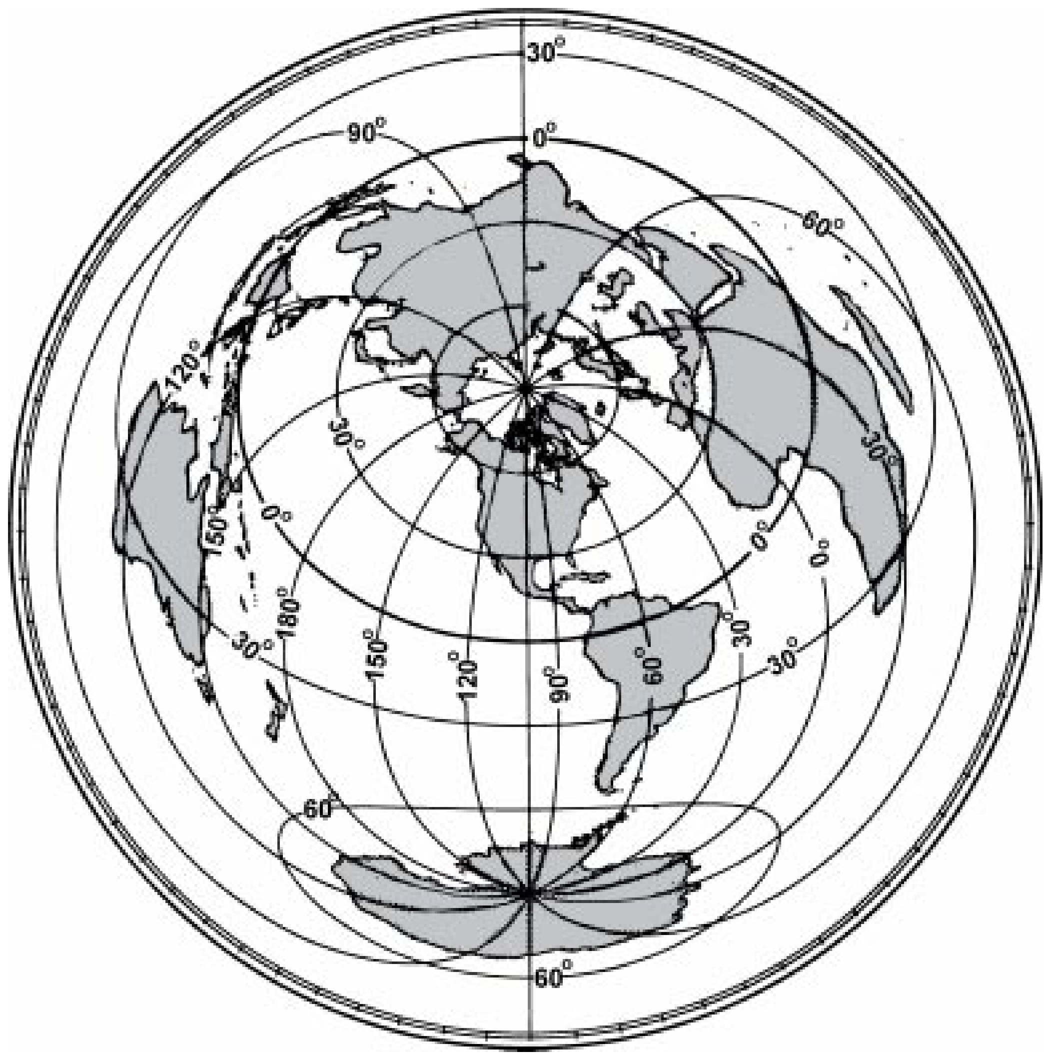


Figure 319. An azimuthal equidistant map of the world with the point of tangency latitude 40°N, longitude 100°W.

POLAR CHARTS

320. Polar Projections

Special consideration is given to the selection of projections for polar charts because the familiar projections become special cases with unique features.

In the case of cylindrical projections in which the axis of the cylinder is parallel to the polar axis of the earth, distortion becomes excessive and the scale changes rapidly. Such projections cannot be carried to the poles. However, both the transverse and oblique Mercator projections are used.

Conic projections with their axes parallel to the earth's polar axis are limited in their usefulness for polar charts because parallels of latitude extending through a full 360° of longitude appear as arcs of circles rather than full circles. This is because a cone, when cut along an element and flattened, does not extend through a full 360° without stretching or resuming its former conical shape. The usefulness of such projections is also limited by the fact that the pole appears as an arc of a circle instead of a point. However, by using a parallel very near the pole as the higher standard parallel, a conic projection with two standard parallels can be made. This requires little stretching to complete the circles of the parallels and eliminate that of the pole. Such a projection, called a **modified Lambert conformal** or **Ney's projection**, is useful for polar charts. It is particularly familiar to those accustomed to using the ordinary Lambert conformal charts in lower latitudes.

Azimuthal projections are in their simplest form when tangent at a pole. This is because the meridians are straight lines intersecting at the pole, and parallels are concentric circles with their common center at the pole. Within a few

degrees of latitude of the pole they all look similar; however, as the distance becomes greater, the spacing of the parallels becomes distinctive in each projection. In the polar azimuthal equidistant it is uniform; in the polar stereographic it increases with distance from the pole until the equator is shown at a distance from the pole equal to twice the length of the radius of the earth; in the polar gnomonic the increase is considerably greater, becoming infinity at the equator; in the polar orthographic it decreases with distance from the pole (Figure 320). All of these but the last are used for polar charts.

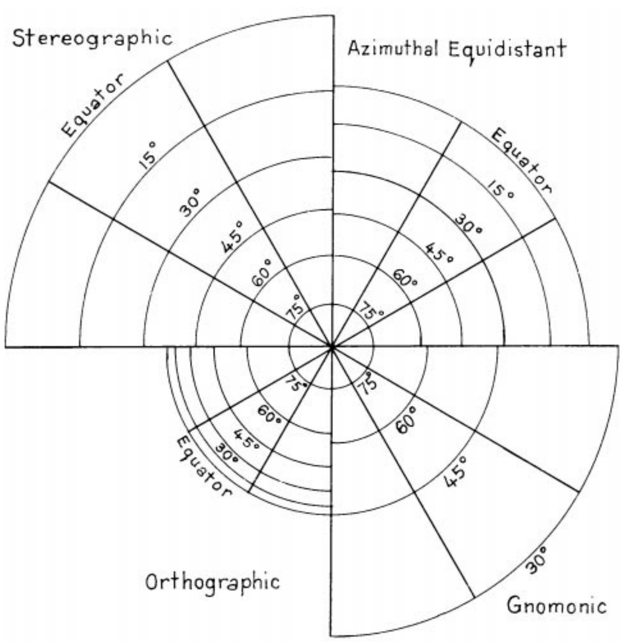


Figure 320. Expansion of polar azimuthal projections.

321. Selection Of A Polar Projection

The principal considerations in the choice of a suitable projection for polar navigation are:

1. Conformality: When the projection represents angles correctly, the navigator can plot directly on the chart.
2. Great circle representation: Because great circles are more useful than rhumb lines at high altitudes, the projection should represent great circles as straight lines.
3. Scale variation: The projection should have a constant scale over the entire chart.
4. Meridian representation: The projection should show straight meridians to facilitate plotting and grid navigation
5. Limits: Wide limits reduce the number of projections needed to a minimum.

The projections commonly used for polar charts are the modified Lambert conformal, gnomonic, stereographic, and azimuthal equidistant. All of these projections are similar near the pole. All are essentially conformal, and a great circle on each is nearly a straight line.

As the distance from the pole increases, however, the distinctive features of each projection become important. The modified Lambert conformal projection is virtually conformal over its entire extent. The amount of its scale distortion is comparatively little if it is carried only to about 25° or 30° from the pole. Beyond this, the distortion increases rapidly. A great circle is very nearly a straight line anywhere on the chart. Distances and directions can be measured directly on the chart in the same manner as on a Lambert conformal chart. However, because this projection is not strictly conformal, and on it great circles are not exactly represented by straight lines, it is not suited for highly accurate work.

The polar gnomonic projection is the one polar projection on which great circles are exactly straight lines. However, a complete hemisphere cannot be represented upon a plane because the radius of 90° from the center would become infinity.

The polar stereographic projection is conformal over its entire extent, and a straight line closely approximates a great circle. See Figure 321. The scale distortion is not excessive for a considerable distance from the pole, but it is greater than that of the modified Lambert conformal projection.

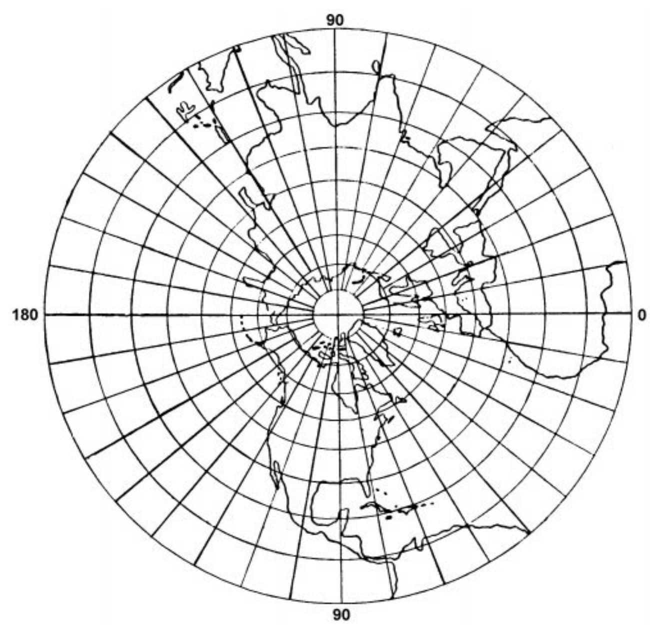


Figure 321. Polar stereographic projection.

The polar azimuthal equidistant projection is useful for showing a large area such as a hemisphere because there is

no expansion along the meridians. However, the projection is not conformal and distances cannot be measured accurately in any but a north-south direction. Great circles other than the meridians differ somewhat from straight lines. The equator is a circle centered at the pole.

The two projections most commonly used for polar charts are the modified Lambert conformal and the polar stereographic. When a directional gyro is used as a directional reference, the track of the craft is approximately a great circle. A desirable chart is one on which a great circle is represented as a straight line with a constant scale and with angles correctly represented. These requirements are not met entirely by any single projection, but they are approximated by both the modified Lambert conformal and the polar stereographic. The scale is more nearly constant on the former, but the projection is not strictly conformal. The polar stereographic is conformal, and its maximum scale variation can be reduced by using a plane which intersects the earth at some parallel intermediate between the pole and the lowest parallel. The portion within this standard parallel is compressed, and that portion outside is expanded.

The selection of a suitable projection for use in polar regions depends upon mission requirements. These requirements establish the relative importance of various features. For a relatively small area, any of several projections is suitable. For a large area, however, the choice is more difficult. If grid directions are to be used, it is important that all units in related operations use charts on the same projection, with the same standard parallels, so that a single grid direction exists between any two points. Nuclear powered submarine operations under the polar icecap have increased the need for grid directions in marine navigation.

SPECIAL CHARTS

322. Plotting Sheets

Position plotting sheets are “charts” designed primarily for open ocean navigation, where land, visual aids to navigation, and depth of water are not factors in navigation. They have a latitude and longitude graticule, and they may have one or more compass roses. The meridians are usually unlabeled, so a plotting sheet can be used for any longitude. Plotting sheets on Mercator projection are specific to latitude, and the navigator should have enough aboard for all latitudes for his voyage. Plotting sheets are less expensive than charts.

One use of a plotting sheet may occur in the event of an emergency when all charts have been lost or are otherwise unavailable. Directions on how to construct plotting sheets suitable for emergency purposes are given in Chapter 26, Emergency Navigation.

323. Grids

No system exists for showing the surface of the earth on a plane without distortion. Moreover, the appearance of the surface varies with the projection and with the relation of that surface area to the point of tangency. One may want to identify a location or area simply by alpha-numeric rectangular coordinates. This is accomplished with a **grid**. In its usual form this consists of two series of lines drawn perpendicularly on the chart, marked by suitable alpha-numeric designations.

A grid may use the rectangular graticule of the Mercator projection or a set of arbitrary lines on a particular projection. **The World Geodetic Reference System (GEOREF)** is a method of designating latitude and longitude by a system of letters and numbers instead of by angular measure. It is not, therefore, strictly a grid. It is useful for operations extending over a wide area. Examples of the second type of grid are the **Universal Transverse Mercator (UTM)** grid, the **Universal Polar Stereographic (UPS)** grid, and the **Temporary Geographic Grid (TGG)**. Since these systems are used primarily by military forces, they are sometimes called military grids.

CHART SCALES

324. Types Of Scales

The **scale** of a chart is the ratio of a given distance on the chart to the actual distance which it represents on the earth. It may be expressed in various ways. The most common are:

1. A simple ratio or fraction, known as the **representative fraction**. For example, 1:80,000 or 1/80,000 means that one unit (such as a meter) on the chart represents 80,000 of the same unit on the surface of the earth. This scale is sometimes called the **natural** or **fractional** scale.
2. A **statement** that a given distance on the earth equals a given measure on the chart, or vice versa. For example, “30 miles to the inch” means that 1 inch on the chart represents 30 miles of the earth’s surface. Similarly, “2 inches to a mile” indicates that 2 inches on the chart represent 1 mile on the earth. This is sometimes called the **numerical scale**.
3. A line or bar called a **graphic scale** may be drawn at a convenient place on the chart and subdivided into nautical miles, meters, etc. All charts vary somewhat

in scale from point to point, and in some projections the scale is not the same in all directions about a single point. A single subdivided line or bar for use over an entire chart is shown only when the chart is of such scale and projection that the scale varies a negligible amount over the chart, usually one of about 1:75,000 or larger. Since 1 minute of latitude is very nearly equal to 1 nautical mile, the latitude scale serves as an approximate graphic scale. On most nautical charts the east and west borders are subdivided to facilitate distance measurements.

On a Mercator chart the scale varies with the latitude. This is noticeable on a chart covering a relatively large distance in a north-south direction. On such a chart the border scale near the latitude in question should be used for measuring distances.

Of the various methods of indicating scale, the graphical method is normally available in some form on the chart. In addition, the scale is customarily stated on charts on which the scale does not change appreciably over the chart.

The ways of expressing the scale of a chart are readily interchangeable. For instance, in a nautical mile there are about 72,913.39 inches. If the natural scale of a chart is 1:80,000, one inch of the chart represents 80,000 inches of the earth, or a little more than a mile. To find the exact amount, divide the scale by the number of inches in a mile, or 80,000/72,913.39 = 1.097. Thus, a scale of 1:80,000 is the same as a scale of 1.097 (or approximately 1.1) miles to an inch. Stated another way, there are: 72,913.39/80,000 = 0.911 (approximately 0.9) inch to a mile. Similarly, if the scale is 60 nautical miles to an inch, the representative fraction is 1:(60 x 72,913.39) = 1:4,374,803.

A chart covering a relatively large area is called a **small-scale chart** and one covering a relatively small area is called a **large-scale chart**. Since the terms are relative, there is no sharp division between the two. Thus, a chart of scale 1:100,000 is large scale when compared with a chart of 1:1,000,000 but small scale when compared with one of 1:25,000.

As scale decreases, the amount of detail which can be shown decreases also. Cartographers selectively decrease the detail in a process called **generalization** when producing small scale charts using large scale charts as sources. The amount of detail shown depends on several factors, among them the coverage of the area at larger scales and the intended use of the chart.

325. Chart Classification By Scale

Charts are constructed on many different scales, ranging from about 1:2,500 to 1:14,000,000. Small-scale charts covering large areas are used for route planning and for offshore navigation. Charts of larger scale, covering smaller areas, are used as the vessel approaches land. Several methods of classifying charts according to scale are used in various nations. The following classifications of nautical charts are used by the National Ocean Service.

Sailing charts are the smallest scale charts used for planning, fixing position at sea, and for plotting the dead reckoning while proceeding on a long voyage. The scale is generally smaller than 1:600,000. The shoreline and topography are generalized and only offshore soundings, the principal navigational lights, outer buoys, and landmarks visible at considerable distances are shown.

General charts are intended for coastwise navigation outside of outlying reefs and shoals. The scales range from about 1:150,000 to 1:600,000.

Coastal charts are intended for inshore coastwise navigation, for entering or leaving bays and harbors of considerable width, and for navigating large inland waterways. The scales range from about 1:50,000 to 1:150,000.

Harbor charts are intended for navigation and anchorage in harbors and small waterways. The scale is generally larger than 1:50,000.

In the classification system used by the Defense Mapping Agency Hydrographic/Topographic Center, the sailing charts are incorporated in the general charts classification (smaller than about 1:150,000); those coast charts especially useful for approaching more confined waters (bays, harbors) are classified as approach charts. There is considerable overlap in these designations, and the classification of a chart is best determined by its use and by its relationship to other charts of the area. The use of insets complicates the placement of charts into rigid classifications.

CHART ACCURACY

326. Factors Relating To Accuracy

The accuracy of a chart depends upon the accuracy of the hydrographic surveys used to compile it and the suitability of its scale for its intended use.

Estimate the accuracy of a chart's surveys from the source notes given in the title of the chart. If the chart is based upon very old surveys, use it with caution. Many early surveys were inaccurate because of the technological limitations of the surveyor.

The number of soundings and their spacing indicates the completeness of the survey. Only a small fraction of the soundings taken in a thorough survey are shown on the chart, but sparse or unevenly distributed soundings indicate that the survey was probably not made in detail. See Figure 326a and Figure 326b Large blank areas or absence of depth

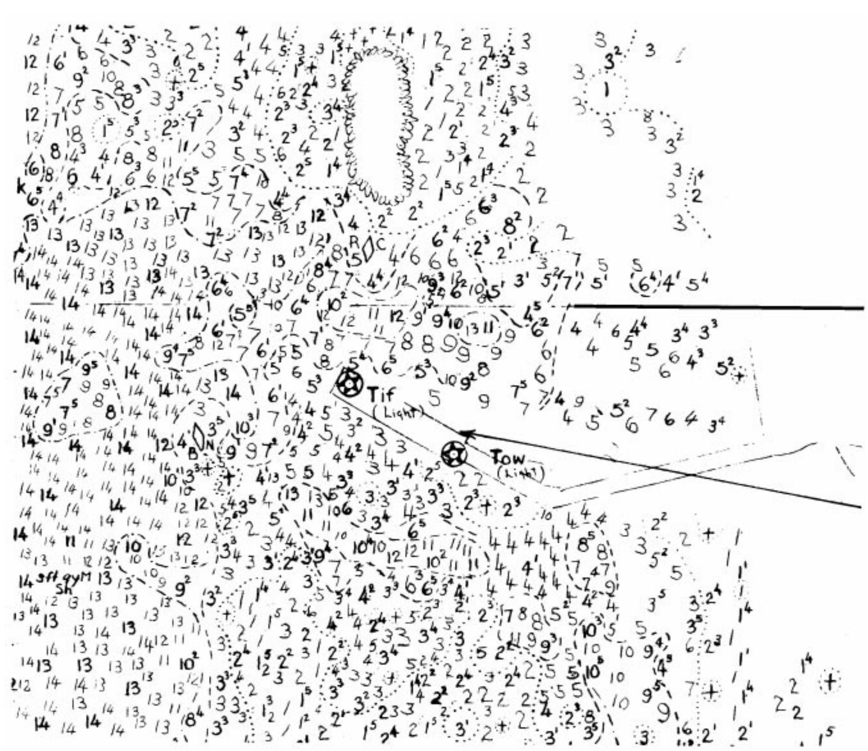


Figure 326a. Part of a “boat sheet,” showing the soundings obtained in a survey.

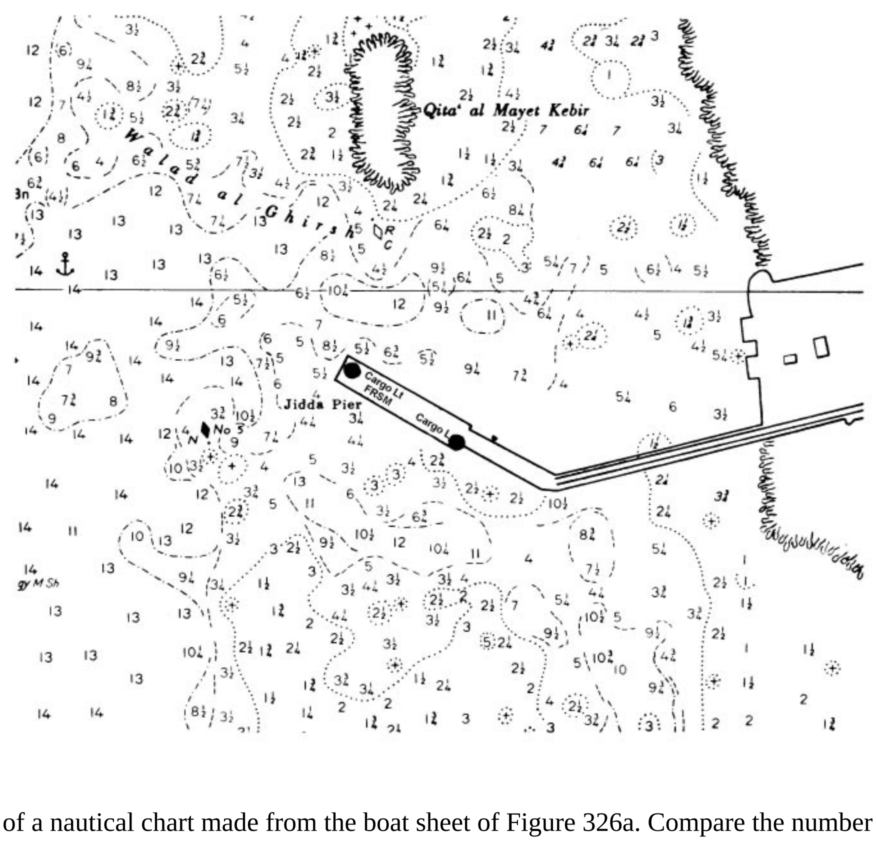


Figure 326b. Part of a nautical chart made from the boat sheet of Figure 326a. Compare the number of soundings in the two figures.

contours generally indicate lack of soundings in the area. Operate in an area with sparse sounding data only if operationally required and then only with the most extreme caution. Run the echo sounder continuously and operate at a reduced speed. Sparse sounding information does not necessarily indicate an incomplete survey. Relatively few soundings are shown when there is a large number of depth contours, or where the bottom is flat, or gently and evenly sloping. Additional soundings are shown when they are helpful in indicating the uneven character of a rough bottom.

Even a detailed survey may fail to locate every rock or pinnacle. In waters where they might be located, the best method for finding them is a wire drag survey. Areas that have been dragged may be indicated on the chart by limiting lines and green or purple tint and a note added to show the effective depth at which the drag was operated.

Changes in bottom contours are relatively rapid in areas such as entrances to harbors where there are strong currents or heavy surf. Similarly, there is sometimes a tendency for dredged channels to shoal, especially if they are surrounded by sand or mud, and cross currents exist. Charts often contain notes indicating the bottom contours are known to change rapidly.

The same detail cannot be shown on a small-scale chart as on a large scale chart. On small-scale charts, detailed information is omitted or "generalized" in the areas covered by larger scale charts. The navigator should use the largest scale chart available for the area in which he is operating, especially when operating in the vicinity of hazards.

Charting agencies continually evaluate both the detail and the presentation of data appearing on a chart. Development of a new navigational aid may render previous charts inadequate. The development of radar, for example, required upgrading charts which lacked the detail required for reliable identification of radar targets.

After receiving a chart, the user is responsible for keeping it updated. Mariners reports of errors, changes, and suggestions are useful to charting agencies. Even with modern automated data collection techniques, there is no substitute for on-sight observation of hydrographic conditions by experienced mariners. This holds true especially in less frequently traveled areas of the world.

CHART READING

327. Chart Dates

NOS charts have two dates. At the top center of the chart is the date of the *first edition* of the chart. In the lower left corner of the chart is the *current* edition number and date. This date shows the latest date through which Notice to Mariners were applied to the chart. Any subsequent change will be printed in the Notice to Mariners. Any notices which accumulate between the chart date and the announcement date in the Notice to Mariners will be given with the announcement. Comparing the dates of the first and current editions gives an indication of how often thechart is updated. Charts of busy areas are updated more frequently than those of less traveled areas. This interval may vary from 6 months to more than ten years for NOS charts. This update interval may be much longer for certain DMAHTC charts in remote areas.

New editions of charts are both demand and source driven. Receiving significant new information may or may not initiate a new edition of a chart, depending on the demand for that chart. If it is in a sparsely-traveled area, other priorities may delay a new edition for several years. Conversely, a new edition may be printed without the receipt of significant new data if demand for the chart is high and stock levels are low. Notice to Mariners corrections are always included on new editions.

DMAHTC charts have the same two dates as the NOS charts; the current chart edition number and date is given in the lower left corner. Certain DMAHTC charts are reproductions of foreign charts produced under joint agreements with a number of other countries. These charts, even though of recent date, may be based on foreign charts of considerably earlier date. Further, new editions of the foreign chart will not necessarily result in a new edition of the DMAHTC reproduction. In these cases, the foreign chart is the better chart to use.

A **revised** or **corrected print** contains corrections which have been published in Notice to Mariners. These corrected prints do not supersede a current edition. The date of the revision is given, along with the latest Notice to Mariners to which the chart has been corrected.

328. Title Block

See Figure 328. The chart title block should be the first thing a navigator looks at when receiving a new edition chart. The title itself tells what area the chart covers. The chart's scale and projection appear below the title. The chart will give both vertical and horizontal datums and, if necessary, a datum conversion note. Source notes or diagrams will list the date of surveys and other charts used in compilation.

329. Shoreline

The shoreline shown on nautical charts represents the

BALTIC SEA

GERMANY—NORTH COAST

DAHMESHÖVED TO WISMAR

From German Surveys

SOUNDINGS IN METERS

reduced to the approximate level of Mean Sea Level

HEIGHTS IN METERS ABOVE MEAN SEA LEVEL

MERCATOR PROJECTION

EUROPEAN DATUM

SCALE 1:50,000

Figure 328. A chart title block.

line of contact between the land and water at a selected vertical datum. In areas affected by tidal fluctuations, this is usually the mean high-water line. In confined coastal waters of diminished tidal influence, a mean water level line may be used. The shoreline of interior waters (rivers, lakes) is usually a line representing a specified elevation above a selected datum. A shoreline is symbolized by a heavy line. A broken line indicates that the charted position is approximate only. The nature of the shore may be indicated.

If the low water line differs considerably from the high water line, then a dotted line represents the low water line. If the bottom in this area is composed of mud, sand, gravel or stones, the type of material will be indicated. If the bottom is composed of coral or rock, then the appropriate symbol will be used. The area alternately covered and uncovered may be shown by a tint which is usually a combination of the land and water tint.

The apparent shoreline shows the outer edge of marine vegetation where that limit would appear as shoreline to the mariner. It is also used to indicate where marine vegetation prevents the mariner from defining the shoreline. A light line symbolizes this shoreline. A broken line marks the inner edge when no other symbol (such as a cliff or levee) furnishes such a limit. The combined land-water tint or the land tint marks the area between inner and outer limits.

330. Chart Symbols

Much of the information contained on charts is shown by symbols. These symbols are not shown to scale, but they indicate the correct position of the feature to which they refer. The standard symbols and abbreviations used on charts published by the United States of America are shown in ***Chart No. 1, Nautical Chart Symbols and Abbreviations***. See Figure 330.

Electronic chart symbols are, within programming and display limits, much the same as printed ones. The less expensive electronic charts have less extensive symbol libraries, and the screen's resolution may affect the presentation detail.

Most of the symbols and abbreviations shown in U.S. Chart No. 1 agree with recommendations of the International Hydrographic Organization (IHO). The layout is explained in the general remarks section of Chart No. 1.

The symbols and abbreviations on any given chart may differ somewhat from those shown in Chart No. 1. In addition, foreign charts may use different symbology. When using a foreign chart, the navigator should have available the Chart No. 1 from the country which produced the chart.

Chart No. 1 is organized according to subject matter, with each specific subject given a letter designator. The general subject areas are General, Topography, Hydrography, Aids and Services, and Indexes. Under each heading, letter designators further define subject areas, and individual numbers refer to specific symbols.

Information in Chart No. 1 is arranged in columns. The first column contains the IHO number code for the symbol in question. The next two columns show the symbol itself, in NOS and NIMAformats. If the formats are the same, the two columns are combined into one. The next column is a text description of the symbol, term, or abbreviation. The next column contains the IHO standard symbol. The last column shows certain symbols used on foreign reproduction charts produced by NIMA.

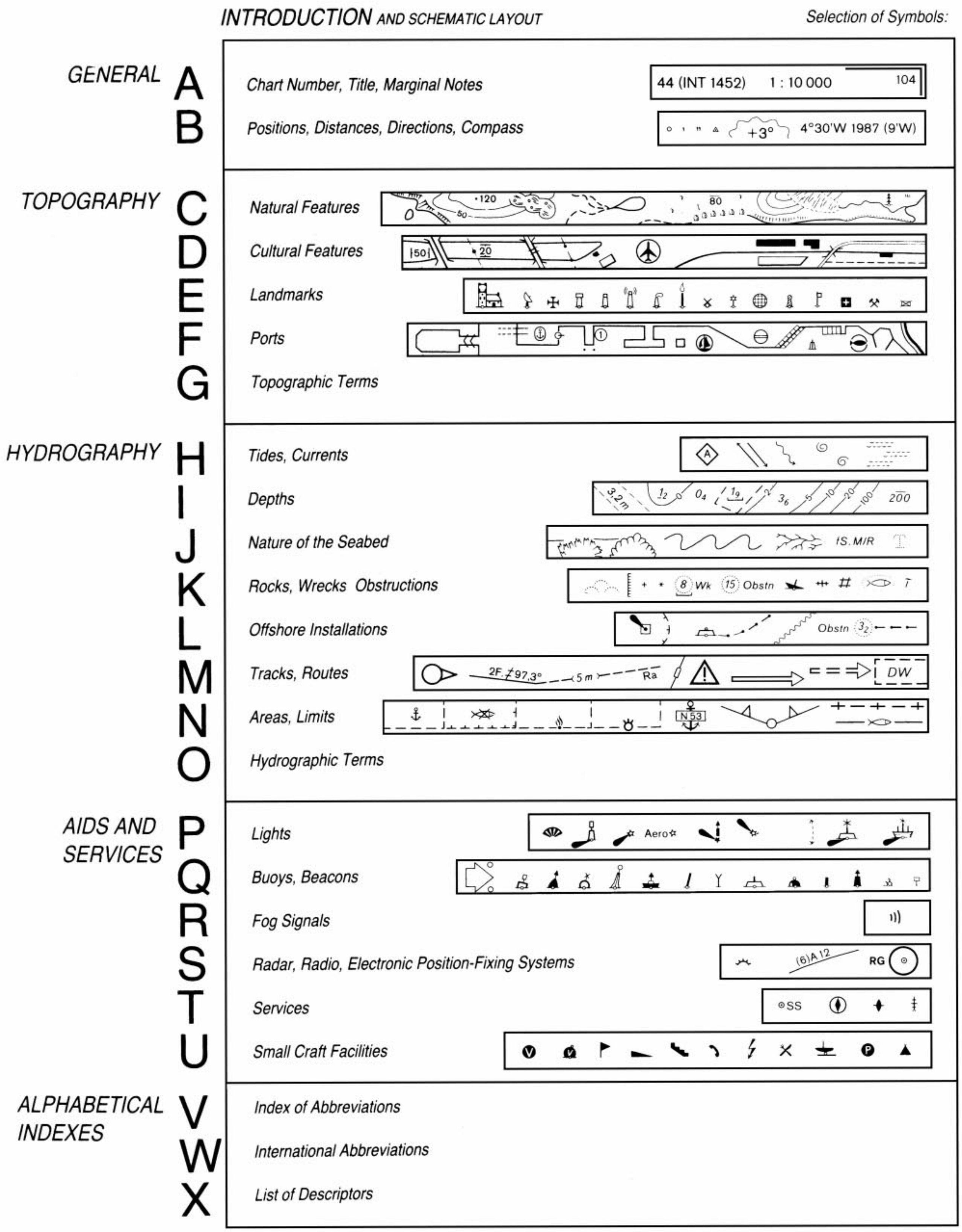


Figure 330. Contents of U.S. Chart No. 1.

331. Lettering

Except on some modified reproductions of foreign charts, cartographers have adopted certain lettering standards. Vertical type is used for features which are dry at high water and not affected by movement of the water; slanting type is used for underwater and floating features.

There are two important exceptions to the two general rules listed above. Vertical type is not used to represent heights above the waterline, and slanting type is not used to indicate soundings, except on metric charts. Section 332 below discusses the conventions for indicating soundings.

Evaluating the type of lettering used to denote a feature, one can determine whether a feature is visible at high tide. For instance, a rock might bear the title " Rock" whether or not it extends above the surface. If the name is given in vertical letters, the rock constitutes a small islet; if in slanting type, the rock constitutes a reef, covered at high water.

332. Soundings

Charts show soundings in several ways. Numbers denote individual soundings. These numbers may be either vertical or slanting; both may be used on the same chart, distinguishing between data based upon different U.S. and foreign surveys, different datums, or smaller scale charts.

Large block letters at the top and bottom of the chart indicate the unit of measurement used for soundings. SOUNDINGS IN FATHOMS indicates soundings are in fathoms or fathoms and fractions. SOUNDINGS IN FATHOMS AND FEET indicates the soundings are in fathoms and feet. A similar convention is followed when the soundings are in meters or meters and tenths.

A **depth conversion scale** is placed outside the neatline on the chart for use in converting charted depths to feet, meters, or fathoms. "No bottom" soundings are indicated by a number with a line over the top and a dot over the line. This indicates that the spot was sounded to the depth indicated without reaching the bottom. Areas which have been wire dragged are shown by a broken limiting line, and the clear effective depth is indicated, with a characteristic symbol under the numbers. On NIMA charts a purple or green tint is shown within the swept area.

Soundings are supplemented by **depth contours**, lines connecting points of equal depth. These lines present a picture of the bottom. The types of lines used for various depths are shown in Section I of Chart No. 1. On some charts depth contours are shown in solid lines; the depth represented by each line is shown by numbers placed in breaks in the lines, as with land contours. Solid line depth contours are derived from intensively developed hydrographic surveys. A broken or indefinite contour is substituted for a solid depth contour whenever the reliability of the contour is questionable.

Depth contours are labeled with numerals in the unit of measurement of the soundings. A chart presenting a more detailed indication of the bottom configuration with fewer numerical soundings is useful when bottom contour navigating. Such a chart can be made only for areas which have undergone a detailed survey

Shoal areas often are given a blue tint. Charts designed to give maximum emphasis to the configuration of the bottom show depths beyond the 100-fathom curve over the entire chart by depth contours similar to the contours shown on land areas to indicate graduations in height. These are called **bottom contour** or **bathymetric charts**.

On electronic charts, a variety of other color schemes may be used, according to the manufacturer of the system. Color perception studies are being used to determine the best presentation.

The side limits of dredged channels are indicated by broken lines. The project depth and the date of dredging, if known, are shown by a statement in or along the channel. The possibility of silting is always present. Local authorities should be consulted for the controlling depth. NOS Charts frequently show controlling depths in a table, which is kept current by the Notice to Mariners.

The chart scale is generally too small to permit all soundings to be shown. In the selection of soundings, least depths are shown first. This conservative sounding pattern provides safety and ensures an uncluttered chart appearance. Steep changes in depth may be indicated by more dense soundings in the area. The limits of shoal water indicated on the chart may be in error, and nearby areas of undetected shallow water may not be included on the chart. Given this possibility, areas where shoal water is known to exist should be avoided. If the navigator must enter an area containing shoals, he must exercise extreme caution in avoiding shallow areas which may have escaped detection. By constructing a "safety range" around known shoals and ensuring his vessel does not approach the shoal any closer than the safety range, the navigator can increase his chances of successfully navigating through shoal water. Constant use of the echo sounder is also important.

333. Bottom Description

Abbreviations listed in Section J of Chart No. 1 are used to indicate what substance forms the bottom. The meaning of these terms can be found in the Glossary of Marine Navigation. Knowing the characteristic of the bottom is most important when anchoring.

334. Depths And Datums

Depths are indicated by soundings or explanatory notes. Only a small percentage of the soundings obtained in a hydrographic survey can be shown on a nautical chart. The least depths are generally selected first, and a pattern built around them to provide a representative indication of bottom relief. In shallow water, soundings may be spaced 0.2 to 0.4 inch apart. The spacing is gradually increased as water deepens, until a spacing of 0.8 to 1.0 inch is reached in deeper waters offshore. Where a sufficient number of soundings are available to permit adequate interpretation,

depth curves are drawn in at selected intervals.

All depths indicated on charts are reckoned from a selected level of the water, called the **chart sounding datum**. The various chart datums are explained in Chapter 9, Tides and Tidal Currents. On charts made from surveys conducted by the United States, the chart datum is selected with regard to the tides of the region. Depths shown are the least depths to be expected under average conditions. On charts based on foreign charts and surveys the datum is that of the original authority. When it is known, the datum used is stated on the chart. In some cases where the chart is based upon old surveys, particularly in areas where the range of tide is not great, the sounding datum may not be known.

For most National Ocean Service charts of the United States and Puerto Rico, the chart datum is mean lower low water. Most Defense Mapping Agency Hydrographic/Topographic Center charts are based upon mean low water, mean lower low water, or mean low water springs. The chart datum for charts published by other countries varies greatly, but is usually lower than mean low water. On charts of the Baltic Sea, Black Sea, the Great Lakes, and other areas where tidal effects are small or without significance, the datum adopted is an arbitrary height approximating the mean water level.

The chart datum of the largest scale chart of an area is generally the same as the reference level from which height of tide is tabulated in the tide tables.

The chart datum is usually only an approximation of the actual mean value, because determination of the actual mean height usually requires a longer series of tidal observations than is usually available to the cartographer. In addition, the heights of the tide vary as a function of time.

Since the chart datum is generally a computed mean or average height at some state of the tide, the depth of water at any particular moment may be less than shown on the chart. For example, if the chart datum is mean lower low water, the depth of water at lower low water will be less than the charted depth about as often as it is greater. A lower depth is indicated in the tide tables by a minus sign (–).

335. Heights

The shoreline shown on charts is generally mean high water. A light’s height is usually reckoned from mean sea level. The heights of overhanging obstructions (bridges, power cables, etc.) are usually reckoned from mean high water. A high water reference gives the mariner the minimum clearance expected.

Since heights are usually reckoned from high water and depths from some form of low water, the reference levels are seldom the same. Except where the range of tide is very large, this is of little practical significance.

336. Dangers

Dangers are shown by appropriate symbols, as indicated in Section K of Chart No. 1.

A rock uncovered at mean high water may be shown as an islet. If an isolated, offlying rock is known to uncover at the sounding datum but to be covered at high water, the chart shows the appropriate symbol for a rock and gives the height above the sounding datum. The chart can give this height one of two ways. It can use a statement such as “Uncov 2 ft.,” or it can indicate the number of feet the rock protrudes above the sounding datum, underline this value, and enclose it in parentheses (i.e. ($\underline{2}$)). A rock which does not uncover is shown by an enclosed figure approximating its dimensions and filled with land tint. It may be enclosed by a dotted depth curve for emphasis.

A tinted, irregular-line figure of approximately true dimensions is used to show a detached coral reef which uncovers at the chart datum. For a coral or rocky reef which is submerged at chart datum, the sunken rock symbol or an appropriate statement is used, enclosed by a dotted or broken line if the limits have been determined.

Several different symbols mark wrecks. The nature of the wreck or scale of the chart determines the correct symbol. A sunken wreck with less than 11 fathoms of water over it is considered dangerous and its symbol is surrounded by a dotted curve. The curve is omitted if the wreck is deeper than 11 fathoms. The safe clearance over a wreck, if known, is indicated by a standard sounding number placed at the wreck. If this depth was determined by a wire drag, the sounding is underscored by the wire drag symbol. An unsurveyed wreck over which the exact depth is unknown but a safe clearance depth is known is depicted with a solid line above the symbol.

Tide rips, eddies, and kelp are shown by symbol or legend.

Piles, dolphins (clusters of piles), snags, and stumps are shown by small circles and a label identifying the type of obstruction. If such dangers are submerged, the letters “Subm” precede the label.

Fish stakes and traps are shown when known to be permanent or hazardous to navigation.

337. Aids To Navigation

Aids to navigation are shown by symbols listed in Sections P through S of Chart No. 1. Abbreviations and additional descriptive text supplement these symbols. In order to make the symbols conspicuous, the chart shows them in size greatly exaggerated relative to the scale of the chart. “Position approximate” circles are used on floating aids to indicate that they have no exact position because they move around their moorings. For most floating aids, the position circle in the symbol marks the approximate location of the anchor or sinker. The actual aid may be displaced from this location by the scope of its mooring.

The type and number of aids to navigation shown on a chart and the amount of information given in their legends varies with the scale of the chart. Smaller scale charts may have fewer aids indicated and less information than larger

scale charts of the same area.

Lighthouses and other navigation lights are shown as black dots with purple disks or as black dots with purple flare symbols. The center of the dot is the position of the light. Some modified facsimile foreign charts use a small star instead of a dot.

On large-scale charts the legend elements of lights are shown in the following order:

Legend	*Example*	*Meaning*
Characteristic	F1(2)	group flashing; 2 flashes
Color	R	red
Period	10s	2 flashes in 10 seconds
Height	80m	80 meters
Range	19M	19 nautical miles
Designation	"6"	light number 6

The legend for this light would appear on the chart:

Fl(2) R 10s 80m 19M "6"

As chart scale decreases, information in the legend is selectively deleted to avoid clutter. The order of deletion is usually height first, followed by period, group repetition interval (e.g. (2)), designation, and range. Characteristic and color will almost always be shown.

Small triangles mark red daybeacons; small squares mark all others. On NIMA charts, pictorial beacons are used when the IALA buoyage system has been implemented. The center of the triangle marks the position of the aid. Except on Intracoastal Waterway charts and charts of state waterways, the abbreviation "Bn" is shown beside the symbol, along with the appropriate abbreviation for color if known. For black beacons the triangle is solid black and there is no color abbreviation. All beacon abbreviations are in vertical lettering.

Radiobeacons are indicated on the chart by a purple circle accompanied by the appropriate abbreviation indicating an ordinary radiobeacon (R Bn) or a radar beacon (Ramark or Racon, for example).

A variety of symbols, determined by both the charting agency and the types of buoys, indicate navigation buoys. IALA buoys (see Chapter 5, Short Range Aids to Navigation) in foreign areas are depicted by various styles of symbols with proper topmarks and colors; the position circle which shows the approximate location of the sinker is at the base of the symbol.

A mooring buoy is shown by one of several symbols as indicated in Chart No. 1. It may be labeled with a berth number or other information.

A buoy symbol with a horizontal line indicates the buoy has horizontal bands. A vertical line indicates vertical stripes; crossed lines indicate a checked pattern. There is no significance to the angle at which the buoy symbol appears on the chart. The symbol is placed so as to avoid interference with other features.

Lighted buoys are indicated by a purple flare from the buoy symbol or by a small purple disk centered on the position circle.

Abbreviations for light legends, type and color of buoy, designation, and any other pertinent information given near the symbol are in slanted type. The letter C, N, or S indicates a can, nun, or spar, respectively. Other buoys are assumed to be pillar buoys, except for special buoys such as spherical, barrel, etc. The number or letter designation of the buoy is given in quotation marks on NOS charts. On other charts they may be given without quotation marks or other punctuation.

Aeronautical lights included in the light lists are shown by the lighthouse symbol, accompanied by the abbreviation "AERO." The characteristics shown depend principally upon the effective range of other navigational lights in the vicinity and the usefulness of the light for marine navigation.

Directional ranges are indicated by a broken or solid line. The solid line, indicating that part of the range intended for navigation, may be broken at irregular intervals to avoid being drawn through soundings. That part of the range line drawn only to guide the eye to the objects to be kept in range is broken at regular intervals. The direction, if given, is expressed in degrees, clockwise from true north.

Sound signals are indicated by the appropriate word in capital letters (HORN, BELL, GONG, or WHIS) or an abbreviation indicating the type of sound. Sound signals of any type except submarine sound signals may be represented by three purple 45° arcs of concentric circles near the top of the aid. These are not shown if the type of signal is listed. The location of a sound signal which does not accompany a visual aid, either lighted or unlighted, is shown by a small circle and the appropriate word in vertical block letters.

Private aids, when shown, are marked "Priv" on NOS charts. Some privately maintained unlighted fixed aids are indicated by a small circle accompanied by the word "Marker," or a larger circle with a dot in the center and the word "MARKER." A privately maintained lighted aid has a light symbol and is accompanied by the characteristics and the usual indication of its private nature. Private aids should be used with caution.

A light sector is the sector or area bounded by two radii and the arc of a circle in which a light is visible or in which it has a distinctive color different from that of adjoining sectors. The limiting radii are indicated on the chart by dotted or dashed lines. Sector colors are indicated by words spelled out if space permits, or by abbreviations (W, R, etc.) if it does not. Limits of light sectors and arcs of visibility as observed from a vessel are given in the light lists, in clockwise order.

338. Land Areas

The amount of detail shown on the land areas of nautical charts depends upon the scale and the intended purpose of the chart. Contours, form lines, and shading indicate relief.

Contours are lines connecting points of equal elevation. Heights are usually expressed in feet (or in meters with means for conversion to feet). The interval between contours is uniform over any one chart, except that certain intermediate contours are sometimes shown by broken line. When contours are broken, their locations are approximate.

Form lines are approximations of contours used for the purpose of indicating relative elevations. They are used in areas where accurate information is not available in sufficient detail to permit exact location of contours. Elevations of individual form lines are not indicated on the chart.

Spot elevations are generally given only for summits or for tops of conspicuous landmarks. The heights of spot elevations and contours are given with reference to mean high water when this information is available.

When there is insufficient space to show the heights of islets or rocks, they are indicated by slanting figures enclosed in parentheses in the water area nearby.

339. Cities And Roads

Cities are shown in a generalized pattern that approximates their extent and shape. Street names are generally not charted except those along the waterfront on the largest scale charts. In general, only the main arteries and thoroughfares or major coastal highways are shown on smaller scale charts. Occasionally, highway numbers are given. When shown, trails are indicated by a light broken line. Buildings along the waterfront or individual ones back from the waterfront but of special interest to the mariner are shown on large-scale charts. Special symbols from Chart No. 1 are used for certain kinds of buildings. A single line with cross marks indicates both single and double track railroads. City electric railways are usually not charted. Airports are shown on small-scale charts by symbol and on large-scale charts by the shape of runways. The scale of the chart determines if single or double lines show breakwaters and jetties; broken lines show the submerged portion of these features.

340. Landmarks

Landmarks are shown by symbols in Chart No. 1.

A large circle with a dot at its center is used to indicate that the position is precise and may be used without reservation for plotting bearings. A small circle without a dot is used for landmarks not accurately located. Capital and lower case letters are used to identify an approximate landmark: “Mon,” “Cup,” or “Dome.” The abbreviation “PA” (position approximate) may also appear. An accurate landmark is identified by all capital type (“MON,” “CUP,” “DOME”).

When only one object of a group is charted, its name is followed by a descriptive legend in parenthesis, including the number of objects in the group, for example “(TALLEST OF FOUR)”or “(NORTHEAST OF THREE).”

341. Miscellaneous Chart Features

A measured nautical mile indicated on a chart is accurate to within 6 feet of the correct length. Most measured miles in the United States were made before 1959, when the United States adopted the International Nautical Mile. The new value is within 6 feet of the previous standard length of 6,080.20 feet. If the measured distance differs from the standard value by more than 6 feet, the actual measured distance is stated and the words “measured mile” are omitted.

Periods after abbreviations in water areas are omitted because these might be mistaken for rocks. However, a lower case i or j is dotted.

Commercial radio broadcasting stations are shown on charts when they are of value to the mariner either as landmarks or sources of direction-finding bearings.

Lines of demarcation between the areas in which international and inland navigation rules apply are shown only when they cannot be adequately described in notes on the chart.

Compass roses are placed at convenient locations on Mercator charts to facilitate the plotting of bearings and courses. The outer circle is graduated in degrees with zero at true north. The inner circle indicates magnetic north.

On many NIMA charts magnetic variation is given to the nearest 1' by notes in the centers of compass roses; the annual change is given to the nearest 1' to permit correction of the given value at a later date. On NOS charts, variation is to the nearest 15', updated at each new edition if over three years old. The current practice of NIMA is to give the magnetic variation to the nearest 1', but the magnetic information on new editions is only updated to conform with the latest five year epoch. Whenever a chart is reprinted, the magnetic information is updated to the latest epoch. On other charts, the variation is given by a series of isogonic lines connecting points of equal variation; usually a separate line represents each degree of variation. The line of zero variation is called the agonic line. Many plans and insets show neither compass roses nor isogonic lines, but indicate magnetic information by note. A local magnetic disturbance of sufficient force to cause noticeable deflection of the magnetic compass, called local attraction, is indicated by a note on the chart.

Currents are sometimes shown on charts with arrows giving the directions and figures showing speeds. The information refers to the usual or average conditions. According to tides and weather, conditions at any given time may differ considerably from those shown.

Review chart notes carefully because they provide important information. Several types of notes are used. Those in the margin give such information as chart number, pub-

lication notes, and identification of adjoining charts. Notes in connection with the chart title include information on scale, sources of data, tidal information, soundings, and cautions. Another class of notes covers such topics as local magnetic disturbance, controlling depths of channels, hazards to navigation, and anchorages.

A datum note will show the datum of the chart (See Chapter 2, Geodesy and Datums in Navigation). It may also contain instructions on plotting positions from the WGS 84 or NAD 83 datums on the chart if such a conversion is needed.

Anchorage areas are labeled with a variety of magenta, black, or green lines depending on the status of the area. Anchorage berths are shown as purple circles, with the number or letter assigned to the berth inscribed within the circle. Caution notes are sometimes shown when there are specific anchoring regulations.

Spoil areas are shown within short broken black lines. Spoil areas are tinted blue on NOS charts and labeled. These areas contain no soundings and should be avoided.

Firing and bombing practice areas in the United States territorial and adjacent waters are shown on NOS and NIMA charts of the same area and comparable scale.

Danger areas established for short periods of time are not charted but are announced locally. Most military commands charged with supervision of gunnery and missile firing areas promulgate a weekly schedule listing activated danger areas. This schedule is subjected to frequent change; the mariner should always ensure he has the latest schedule prior to proceeding into a gunnery or missile firing area. Danger areas in effect for longer periods are published in the Notice to Mariners. Any aid to navigation established to mark a danger area or a fixed or floating target is shown on charts.

Traffic separation schemes are shown on standard nautical charts of scale 1:600,000 and larger and are printed in magenta.

A logarithmic time-speed-distance nomogram with an explanation of its application is shown on harbor charts.

Tidal information boxes are shown on charts of scales 1:200,000 and larger for NOS charts, and various scales on DMA charts, according to the source. See Figure 341a.

Tabulations of controlling depths are shown on some National Ocean Service harbor and coastal charts. See Figure 341b.

Study Chart No. 1 thoroughly to become familiar with all the symbols used to depict the wide variety of features on nautical charts.

TIDAL INFORMATION

Place	Position		Height above datum of soundings			
			Mean High Water		Mean Low Water	
	N. Lat.	E. Long.	Higher	Lower	Lower	Higher
			meters	meters	meters	meters
Olongapo	14°49'	120°17'	. . . 0.9 . . .	. . . 0.4 . . .	. . . 0.0 . . .	. . . 0.3 . . .

Figure 341a. Tidal box.

NANTUCKET HARBOR

Tabulated from surveys by the Corps of Engineers - report of June 1972 and surveys of Nov. 1971

Controlling depths in channels entering from seaward in feet at Mean Low Water					Project Dimensions		
Name of Channel	Left outside quarter	Middle half of channel	Right outside quarter	Date of Survey	Width (feet)	Length (naut. miles)	Depth M. L. W. (feet)
Entrance Channel	**11.1**	**15.0**	**15.0**	11 - 71	300	1.2	15

Note.-The Corps of Engineers should be consulted for changing conditions subsequent to the above.

Figure 341b. Tabulations of controlling depths.

REPRODUCTIONS OF FOREIGN CHARTS

342. Modified Facsimiles

Modified facsimile charts are modified reproductions of foreign charts produced in accordance with bilateral international agreements. These reproductions provide the mariner with up-to-date charts of foreign waters. Modified facsimile charts published by DMAHTC are, in general, reproduced with minimal changes, as listed below:

1. The original name of the chart may be removed and replaced by an anglicized version.
2. English language equivalents of names and terms on the original chart are printed in a suitable glossary on the reproduction, as appropriate.
3. All hydrographic information, except bottom characteristics, is shown as depicted on the original chart.
4. Bottom characteristics are as depicted in Chart No. 1, or as on the original with a glossary.
5. The unit of measurement used for soundings is shown in block letters outside the upper and lower neatlines.
6. A scale for converting charted depth to feet, meters, or fathoms is added.
7. Blue tint is shown from a significant depth curve to the shoreline.
8. Blue tint is added to all dangers enclosed by a dotted danger curve, dangerous wrecks, foul areas, obstructions, rocks awash, sunken rocks, and swept wrecks.
9. Caution notes are shown in purple and enclosed in a box.
10. Restricted, danger, and prohibited areas are usually outlined in purple and labeled appropriately.
11. Traffic separation schemes are shown in purple.
12. A note on traffic separation schemes, printed in black, is added to the chart.
13. Wire dragged (swept) areas are shown in purple or green.
14. Corrections are provided to shift the horizontal datum to the World Geodetic System (1984).

INTERNATIONAL CHARTS

343. International Chart Standards

The need for mariners and chart makers to understand and use nautical charts of different nations became increasingly apparent as the maritime nations of the world developed their own establishments for the compilation and publication of nautical charts from hydrographic surveys. Representatives of twenty-two nations formed a Hydrographic Conference in London in 1919. That conference resulted in the establishment of the **International Hydrographic Bureau (IHB)** in Monaco in 1921. Today, the IHB's successor, the **International Hydrographic Organization (IHO)** continues to provide international standards for the cartographers of its member nations. (See Chapter 1, Introduction to Marine Navigation, for a description of the IHO.)

Recognizing the considerable duplication of effort by member states, the IHO in 1967 moved to introduce the first **international chart**. It formed a committee of six member states to formulate specifications for two series of international charts. Eighty-three small-scale charts were approved; responsibility for compiling these charts has subsequently been accepted by the member states' Hydrographic Offices.

Once a Member State publishes an international chart, reproduction material is made available to any other Member State which may wish to print the chart for its own purposes.

International charts can be identified by the letters INT before the chart number and the International Hydrographic Organization seal in addition to other national seals which may appear.

CHART NUMBERING SYSTEM

344. Description Of The Numbering System

NIMA and NOS use a system in which numbers are assigned in accordance with both the scale and geographical area of coverage of a chart. With the exception of certain charts produced for military use only, one- to five-digit numbers are used. With the exception of one-digit numbers, the first digit identifies the area; the number of digits establishes the scale range. The one-digit numbers are used for certain products in the chart system which are not actually charts.

Number of Digits	*Scale*
1	No Scale
2	1:9 million and smaller
3	1:2 million to 1:9 million
4	Special Purpose
5	1:2 million and larger

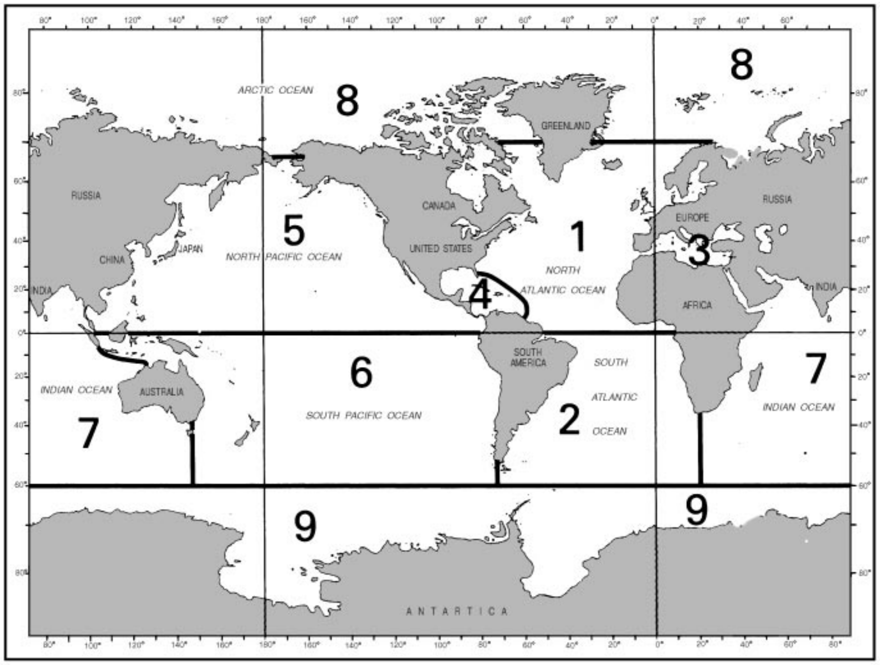


Figure 344a. Ocean basins with region numbers.

Two- and three-digit numbers are assigned to those small-scale charts which depict a major portion of an ocean basin or a large area. The first digit identifies the applicable ocean basin. See Figure 344a. Two-digit numbers are used for charts of scale 1:9,000,000 and smaller. Three-digit numbers are used for charts of scale 1:2,000,000 to 1:9,000,000.

Due to the limited sizes of certain ocean basins, no charts for navigational use at scales of 1:9,000,000 and smaller are published to cover these basins. The otherwise unused two-digit numbers (30 to 49 and 70 to 79) are assigned to special world charts such as chart 33, *Horizontal Intensity of the Earth's Magnetic Field*, chart 42, *Magnetic Variation*, and chart 76, *Standard Time Zone Chart of the World*.

One exception to the scale range criteria for three-digit numbers is the use of three-digit numbers for a series of position plotting sheets. They are of larger scale than 1:2,000,000 because they have application in ocean basins and can be used in all longitudes.

Four-digit numbers are used for non-navigational and special purpose charts, such as chart 5090, *Maneuvering Board*; chart 5101, *Gnomonic Plotting Chart North Atlantic*; and chart 7707, *Omega Plotting Chart*.

Five-digit numbers are assigned to those charts of scale 1:2,000,000 and larger that cover portions of the coastline rather than significant portions of ocean basins. These charts are based on the regions of the nautical chart index. See Figure 344b.

The first of the five digits indicates the region; the second digit indicates the subregion; the last three digits indicate the geographical sequence of the chart within the subregion. Many numbers have been left unused so that any future charts may be placed in their proper geographical sequence.

In order to establish a logical numbering system within the geographical subregions (for the 1:2,000,000 and larger-scale charts), a worldwide skeleton framework of coastal charts was laid out at a scale 1:250,000. This series was used as basic coverage except in areas where a coordinated series at about this scale already existed (such as the coast of Norway where a coordinated series of 1:200,000 charts was available). Within each region, the geographical subregions are numbered counterclockwise around the continents, and within each subregion the basic series also is numbered counterclockwise around the continents. The basic coverage is assigned generally every 20th digit, except that the first 40 numbers in each subregion are reserved for smaller-scale coverage. Charts with scales larger than the basic coverage are assigned one of the 19 numbers following the number assigned to the sheet within which it falls. Figure 344c shows the numbering sequence in Iceland. Note the sequence of numbers around the coast, the direction of numbering, and the numbering of larger scale charts within the limits of smaller scales.

Five-digit numbers are also assigned to the charts produced by other hydrographic offices. This numbering system is applied to foreign charts so that they can be filed in logical sequence with the charts produced by the National Imagery and Mapping Agency and the National Ocean Service.

INDEX OF REGIONS AND SUBREGIONS

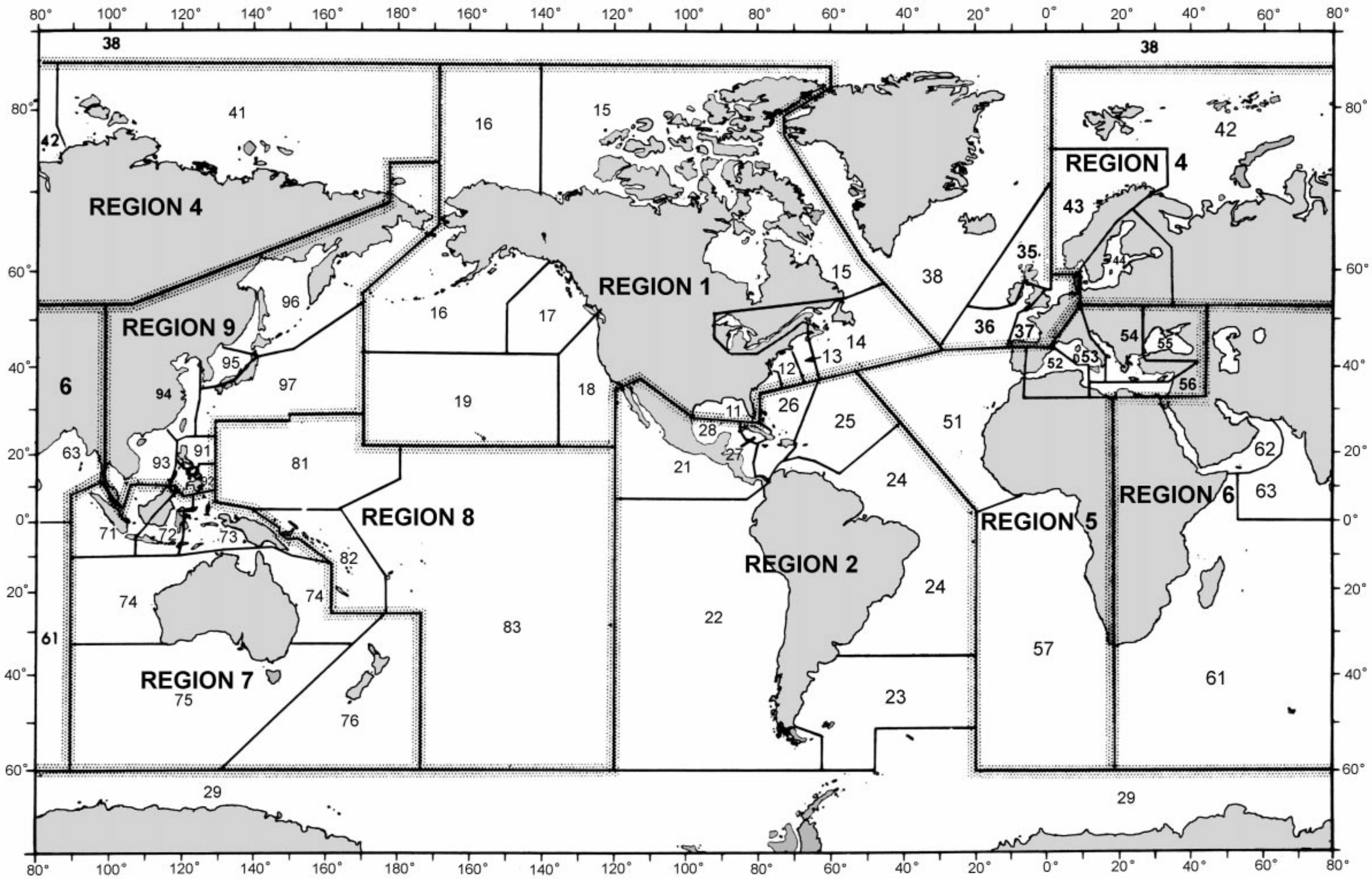


Figure 344b. Regions and subregions of the nautical chart index.

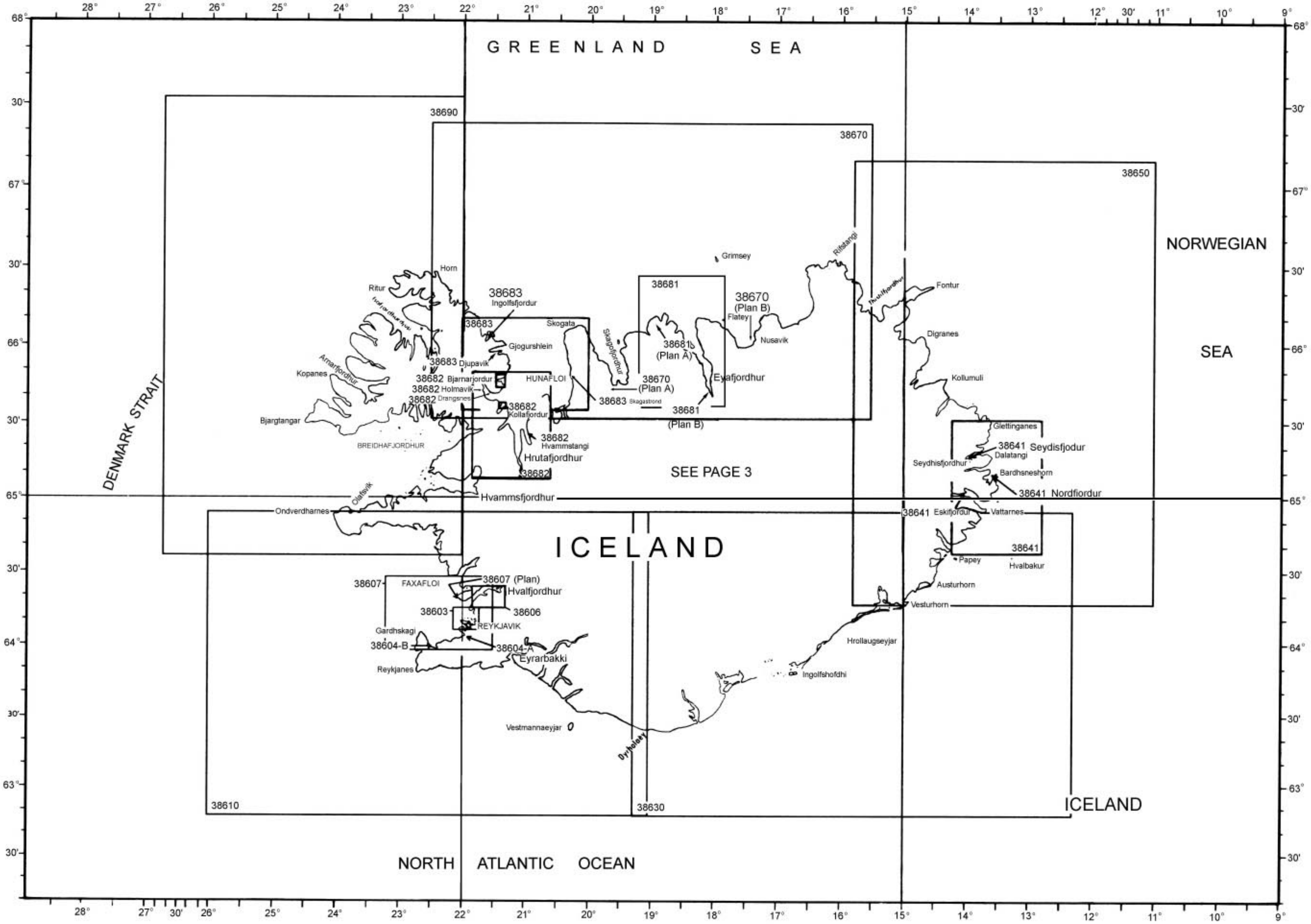


Figure 344c. Chart coverage of Iceland, illustrating the sequence and direction of the U.S. chart numbering system.

345. Exceptions To The System

Exceptions to the numbering system for military needs are as follows:

1. Bottom contour charts are not intended for surface navigation, and do not portray portions of a coastline. They chart parts of the ocean basins. They are identified with a letter plus four digits and are not available to civilian navigators.

2. Combat charts have 6-digit numbers beginning with an “8.” They are not available to civilian navigators.

346. Chart Catalogs

Chart catalogs provide information regarding not only chart coverage, but also a variety of special purpose charts and publications of interest. Keep a corrected chart catalog aboard ship for review by the navigator. The NIMA catalog is available to military navigators. It contains operating area charts and other special products not available for civilian use, but it does not contain any classified listings. The NOS catalogs contain all unclassified civilian-use NOS and NIMA charts. Military navigators receive their nautical charts and publications directly from NIMA; civilian navigators purchase them from NOS sales agents.

347. Stock Numbers

The stock number and bar code are generally found in the lower left corner of a NIMA chart, and in the lower right corner of an NOS chart. The first two digits of the stock number refer to the region and subregion. These are followed by three letters, the first of which refers to the portfolio to which the chart belongs; the second two denote the type of chart: CO for coastal, HA for harbor and approach, and OA for military operating area charts. The last five digits are the actual chart number.

USING CHARTS

348. Preliminary Steps

Upon receiving a new paper chart, verify its announcement in the Notice to Mariners and correct it with all applicable corrections. Read all the chart’s notes; there should be no question about the meanings of symbols or the units in which depths are given. Since the latitude and longitude scales differ considerably on various charts, carefully note those on the chart to be used.

Prepare piloting charts as discussed in Chapter 8 and open ocean transit charts as discussed in Chapter 25.

Place additional information on the chart as required. Arcs of circles might be drawn around navigational lights to indicate the limit of visibility at the height of eye of an observer on the bridge. Notes regarding other information from the light lists, tide tables, tidal current tables, and sailing directions might prove helpful.

The preparation of electronic charts for use is determined by the operator’s manual for the system. If the electronic chart system in use is not IMO-approved, the navigator is required to maintain a concurrent plot on paper charts.

349. Maintaining Paper Charts

A mariner navigating on an uncorrected chart is courting disaster. The chart’s print date reflects the latest Notice to Mariners used to update the chart; responsibility for maintaining it after this date lies with the user. The weekly Notice to Mariners contains information needed for maintaining charts. Radio broadcasts give advance notice of urgent corrections. Local Notice to Mariners should be consulted for inshore areas. The navigator must develop a system to keep track of chart corrections and to ensure that the chart he is using is updated with the latest correction. A convenient way of keeping this record is with a *Chart/Publication Correction Record Card* system. Using this system, the navigator does not immediately update every chart in his portfolio when he receives the Notice to Mariners. Instead, he constructs a card for every chart in his portfolio and notes the correction on this card. When the time comes to use the chart, he pulls the chart and chart’s card, and he makes the indicated corrections on the chart. This system ensures that every chart is properly corrected prior to use.

A *Summary of Corrections*, containing a cumulative listing of previously published Notice to Mariners corrections, is published annually in 5 volumes by NIMA. Thus, to fully correct a chart whose edition date is several years old, the navigator needs only the Summary of Corrections for that region and the notices from that Summary forward; he does not need to obtain notices all the way back to the edition date. See Chapter 4, Nautical Publications, for a description of the Summaries and Notice to Mariners.

When a new edition of a chart is published, it is normally furnished automatically to U.S. Government vessels. It should not be used until it is announced as ready for use in the Notice to Mariners. Until that time, corrections in the Notice apply to the old edition and should not be applied to the new one. When it is announced, a new edition of a chart replaces an older one.

Commercial users and others who don’t automatically receive new editions should obtain new editions from their sales agent. Occasionally, charts may be received or purchased several weeks in advance of their announcement in the Notice to Mariners. This is usually due to extensive rescheming of a chart region and the need to announce groups of charts together to avoid lapses in coverage. The mariner bears the responsibility for ensuring that his charts are the

current edition. The very fact that a new edition has been prepared indicates that there have been changes that cannot adequately be shown by hand corrections.

350. Use And Stowage Of Charts

Use and stow charts carefully. This is especially true with digital charts contained on electronic media. Keep optical and magnetic media containing chart data out of the sun, inside dust covers, and away from magnetic influences. Placing a disk in an inhospitable environment will destroy important data.

Make permanent corrections to paper charts in ink so that they will not be inadvertently erased. Pencil in all other markings so that they can be easily erased without damaging the chart. Lay out and label tracks on charts of frequently-traveled ports in ink. Draw lines and labels no larger than necessary. Do not obscure sounding data or other information when labeling a chart. When a voyage is completed, carefully erase the charts unless there has been a grounding or collision. In this case, preserve the charts without change because they will play a critical role in the investigation.

When not in use, stow charts flat in their proper portfolio. Minimize their folding and properly index them for easy retrieval.

351. Chart Lighting

Mariners often work in a red light environment because red light is least disturbing to night adapted vision. Such lighting seriously affects the appearance of a chart. Before using a chart in red light, test the effect red light has on its markings. Do not outline or otherwise indicate navigational hazards in red pencil because red markings disappear under red light.

The above point cannot be overemphasized; do not highlight danger areas on charts with red markers. Several ships have grounded on charted hazards simply because their conning officers were operating in a red light environment that obscured dangers highlighted on their charts in red pen. Always highlight danger areas on charts with a color that will not disappear in red light.

352. Small-Craft Charts

Although the small-craft charts published by the National Ocean Service are designed primarily for boatmen, these charts at scales of 1:80,000 and larger are in some cases the only charts available of inland waters transited by large vessels. In other cases the small-craft charts may provide a better presentation of navigational hazards than the standard nautical chart because of scale and detail. Therefore, navigators should use these charts in areas where they provide the best coverage.

CHAPTER 4

NAUTICAL PUBLICATIONS

INTRODUCTION

400. Definitions

The navigator uses many information sources when planning and conducting a voyage. These sources include notices to mariners, sailing directions, light lists, tide tables, sight reduction tables, and almanacs. Historically, this information has been found in printed publications; increasingly, it is being integrated into computer-based electronic systems. The navigator must know what information he needs to navigate his ship safely and how to obtain it.

This chapter will refer only to printed publications. If the navigator has access to this data on an electronic database, only his method of access will differ. The publications discussed here form a basic navigation library; the navigator must also obtain all supplementary materials required to navigate his ship safely.

401. Types And Sources Of Publications

While voyage planning and navigating, a mariner must refer to both texts and tables. Examples of text include sailing directions, coast pilots, and notices to mariners. Examples of tables include light lists and sight reduction tables.

Navigational publications are available from many sources. Military customers automatically receive or requisition most required publications. The civilian navigator obtains his publications from a publisher's agent. Larger agents representing many publishers can completely supply a ship's chart and publication library.

NAUTICAL TEXTS

402. Sailing Directions

National Imagery and Mapping Agency *Sailing Directions* consist of 37 **Enroutes** and 10 **Planning Guides**. Planning Guides describe general features of ocean basins; Enroutes describe features of coastlines, ports, and harbors.

Sailing Directions are updated when new data requires extensive revision of an existing text. These data are obtained from several sources, including pilots and foreign Sailing Directions.

One book comprises the Planning Guide and Enroute for Antarctica. This consolidation allows for a more effective presentation of material on this unique area.

The Planning Guides are relatively permanent; by contrast, Sailing Directions (Enroute) are frequently updated. Between updates, both are corrected by the *Notice to Mariners*.

403. Sailing Directions (Planning Guide)

Planning Guides assist the navigator in planning an extensive oceanic voyage. Each of the Guides covers an area determined by an arbitrary division of the world's seas into eight "ocean basins." This division is shown in Figure 403.

A Planning Guide's first chapter contains information about the countries adjacent to the applicable ocean basin. It also covers pratique, pilotage, signals, and shipping regulations. Search and Rescue topics include the location of all lifesaving stations.

The second chapter contains information on the physical environment of an ocean basin. It consists of Ocean Summaries and descriptions of local coastal phenomena. This gives the mariner meteorological and oceanographic information to be considered in planning a route.

The third chapter lists foreign firing danger areas not shown in other NIMA publications. A graphic key identifies Submarine Operating Areas. This chapter also identifies publications listing danger areas and gives pertinent navigation cautions.

The fourth chapter describes recommended steamship routes. To facilitate planning, the publication shows entire routes to foreign ports originating from all major U.S. ports. This chapter also includes all applicable Traffic Separation Schemes.

The fifth and final chapter describes available radionavigation systems and the area's system of lights, beacons, and buoys.

Appendices contain information on buoyage systems, route charts, and area meteorological conditions.

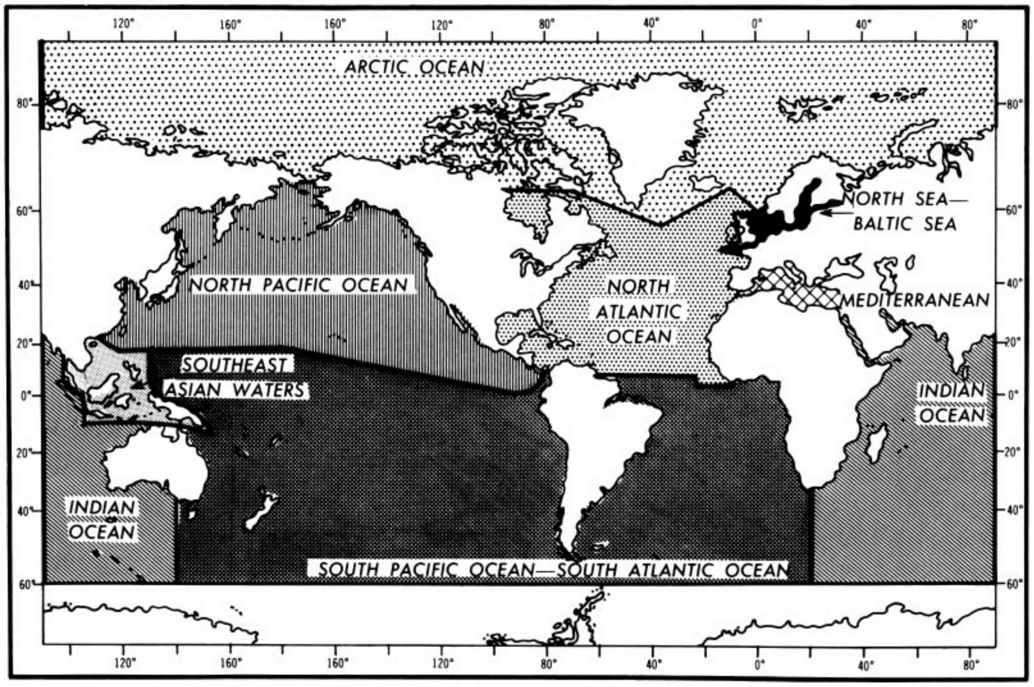


Figure 403. The 8 ocean basins as organized for Sailing Directions (Planning Guides).

404. Sailing Directions (Enroute)

Each volume of the *Sailing Directions* (Enroute) contains numbered sections along a coast or through a strait. Figure 404a illustrates this division. Each sector is discussed in turn. A preface with detailed information about authorities, references, and conventions used in each book precedes the sector discussions. Finally, each book provides conversions between feet, fathoms, and meters.

The Chart Information Graphic, the first item in each chapter, is a graphic key for charts pertaining to a sector. See Figure 404b. The graduation of the border scale of the chartlet enables navigators to identify the largest scale chart for a location and to find a feature listed in the Index-Gazetteer. These graphics are not maintained by *Notice to Mariners*; one should refer to the chart catalog for updated chart listings.

Other graphics may contain special information on local winds and weather, anchorages, significant coastal features, and navigation dangers.

A foreign terms glossary, an appendix of anchorages, and a comprehensive Index-Gazetteer follow the sector discussions. The Index-Gazetteer is an alphabetical listing of described and charted features. The Index lists each feature by geographic coordinates and sector number for use with the graphic key. Features mentioned in the text are listed by page number.

405. Coast Pilots

The National Ocean Service publishes nine *United States Coast Pilots* to supplement nautical charts of U.S. waters. Information comes from field inspections, survey vessels, and various harbor authorities. Maritime officials and pilotage associations provide additional information. *Coast Pilots* provide more detailed information than Sailing Directions because Sailing Directions are intended exclusively for the oceangoing mariner. The *Notice to Mariners* updates *Coast Pilots*.

Each volume contains comprehensive sections on local operational considerations and navigation regulations. Following chapters contain detailed discussions of coastal navigation. An appendix provides information on obtaining additional weather information, communications services, and other data. An index and additional tables complete the volume.

406. Other Nautical Texts

The government publishes several other nautical texts. The Defense Mapping Agency, for example, publishes the *Maneuvering Board Manual* (*Pub. 217*), *The Radar Navigation Manual* (*Pub.1310*) and the *American Practical Navigator* (*Pub. 9*).

The U.S. Coast Guard publishes navigation rules for international and inland waters. This publication, officially known as Commandant Instruction M16672.2b, contains

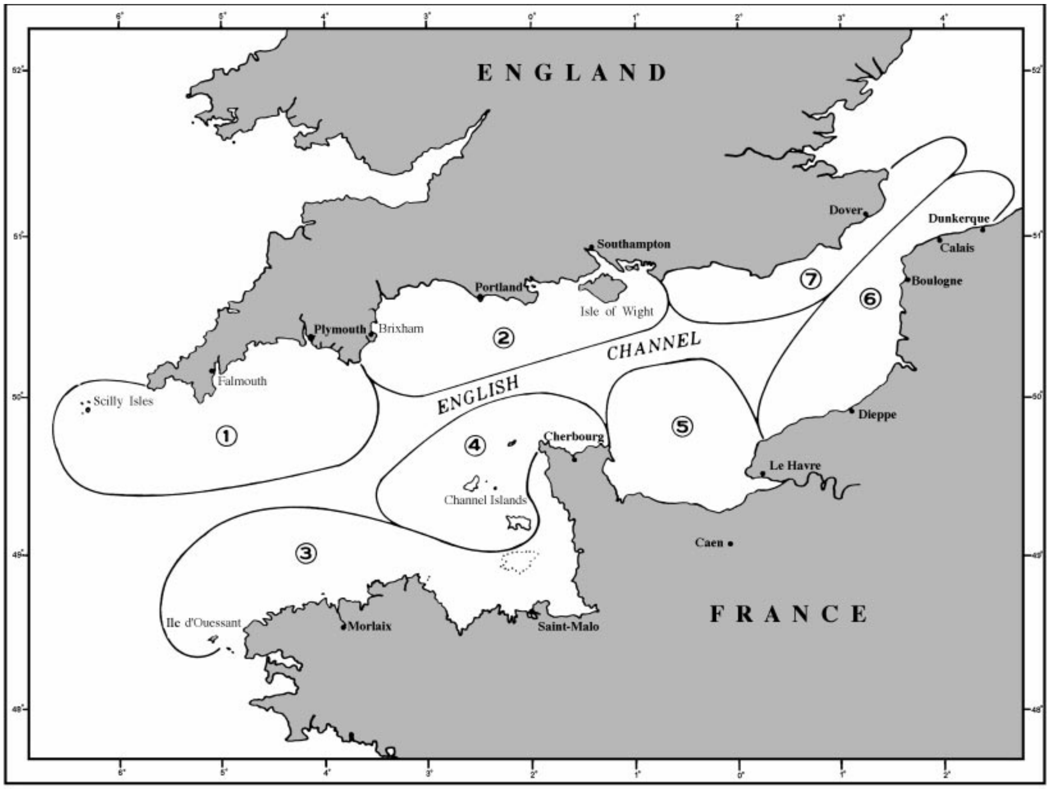
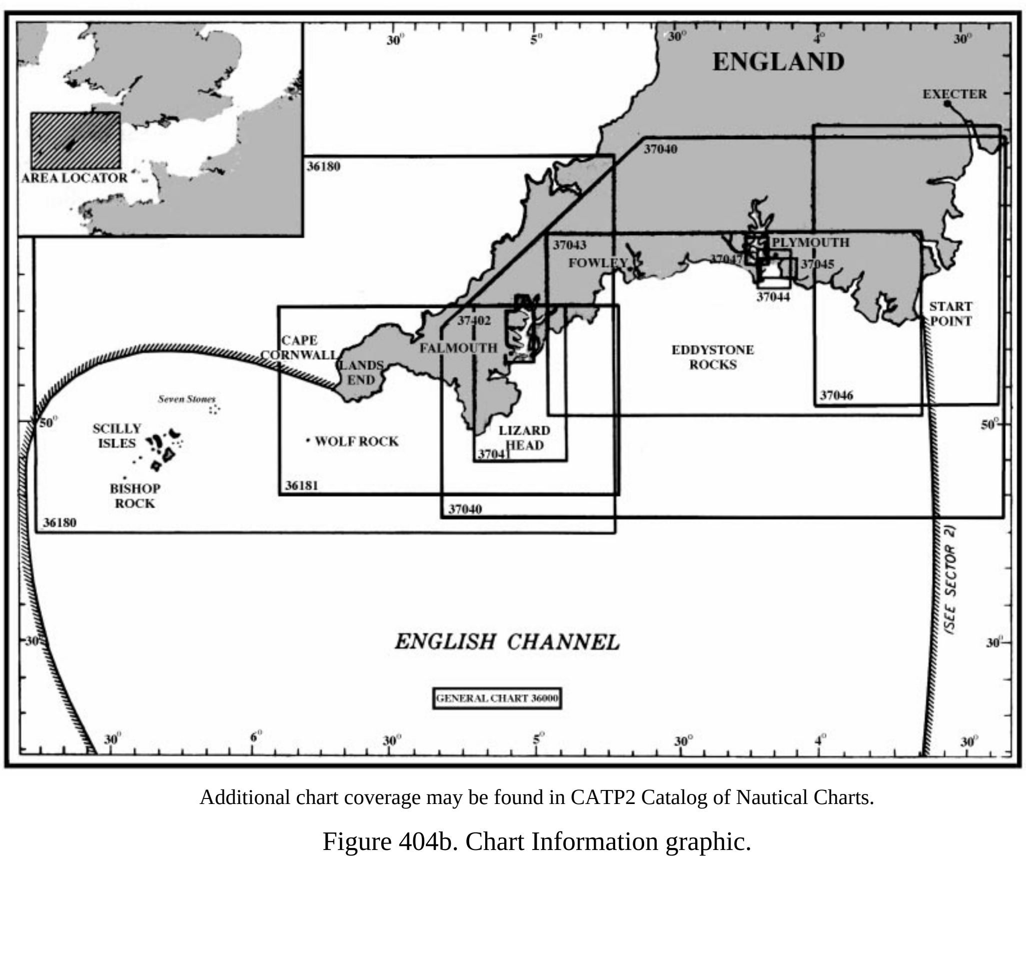


Figure 404a. Sector Limits graphic.



Additional chart coverage may be found in CATP2 Catalog of Nautical Charts.

Figure 404b. Chart Information graphic.

the Inland Navigation Rules enacted in December 1980 and effective on all inland waters of the United States including the Great Lakes, as well as the International Regulations for the Prevention of Collisions at Sea, enacted in 1972 (1972 COLREGS). Mariners should ensure that they have the updated issue. The Coast Guard also publishes comprehensive user's manuals for the Omega, Loran, and GPS navigation systems; *Navigation and Vessel Inspection Circulars*; and the *Chemical Data Guide for Bulk Shipment by Water*.

The Government Printing Office provides several publications on navigation, safety at sea, communications, weather, and related topics. Additionally, it publishes provisions of the Code of Federal Regulations (CFR) relating to maritime matters. A number of private publishers also provide maritime publications.

The International Maritime Organization, International Hydrographic Organization, and other governing international organizations provide information on international navigation regulations. Chapter 1 gives these organizations' addresses. Regulations for various Vessel Traffic Services (VTS), canals, lock systems, and other regulated waterways are published by the authorities which operate them.

USING THE LIGHT LISTS

407. Light Lists

The United States publishes two different light lists. The U.S. Coast Guard publishes the *Light List* for lights in U.S. territorial waters; DMAHTC publishes the *List of Lights* for lights in foreign waters.

Light lists furnish complete information about navigation lights and other navigation aids. They supplement, but do not replace, charts and sailing directions. Consult the chart for the location and light characteristics of all navigation aids; consult the light lists to determine their detailed description.

The *Notice to Mariners* corrects both lists. Corrections which have accumulated since the print date are included in the *Notice to Mariners* as a *Summary of Corrections*. All of these summary corrections, and any corrections published subsequently, should be noted in the "Record of Corrections."

A navigator needs to know both the identity of a light and when he can expect to see it; he often plans the ship's track to pass within a light's range. If lights are not sighted when predicted, the vessel may be significantly off course and standing into danger.

A circle with a radius equal to the visible range of the light usually defines the area in which a light can be seen. On some bearings, however, obstructions may reduce the range. In this case, the obstructed arc might differ with height of eye and distance. Also, lights of different colors may be seen at different distances. Consider these facts both when identifying a light and predicting the range at which it can be seen.

Atmospheric conditions have a major effect on a light's range. Fog, haze, dust, smoke, or precipitation can obscure a light. Additionally, a light can be extinguished. Always report an extinguished light so maritime authorities can issue a warning.

On a dark, clear night, the visual range is limited by either: (1) luminous intensity, or (2) curvature of the earth. Regardless of the height of eye, one cannot see a weak light beyond a certain luminous range. Assuming light travels linearly, an observer located below the light's visible horizon cannot see it. The Distance to the Horizon table gives the distance to the horizon for various heights of eye. The light lists contain a condensed version of this table. Abnormal refraction patterns might change this range; therefore, one cannot exactly predict the range at which a light will be seen.

408. Determining Range And Bearing Of A Light At Initial Sighting

A light's **luminous range** is the maximum range at which an observer can see a light under existing visibility conditions. This luminous range ignores the elevation of the light, the observer's height of eye, the curvature of the earth, and interference from background lighting. It is determined from the known **nominal range** and the existing visibility conditions. The nominal range is the maximum distance at which a light can be seen in weather conditions where visibility is 10 nautical miles.

The U.S. Coast Guard Light List usually lists a light's nominal range. Use the Luminous Range Diagram shown in the Light List and Figure 408a to convert this nominal range to luminous range. Remember that the luminous ranges obtained are approximate because of atmospheric or background lighting conditions. Estimate the meteorological visibility by the Meteorological Optical Range Table, Figure 408b. Next, enter the Luminous Range Diagram with the nominal range on the horizontal nominal range scale. Follow a vertical line until it intersects the curve or reaches the region on the diagram representing the meteorological visibility. Finally, follow a horizontal line from this point or region until it intersects the vertical luminous range scale.

Example 1: *The nominal range of a light as extracted from the Light List is 15 nautical miles.*

Required: *The luminous range when the meteorological visibility is (1) 11 nautical miles and (2) 1 nautical mile.*

Solution: *To find the luminous range when the meteo-*

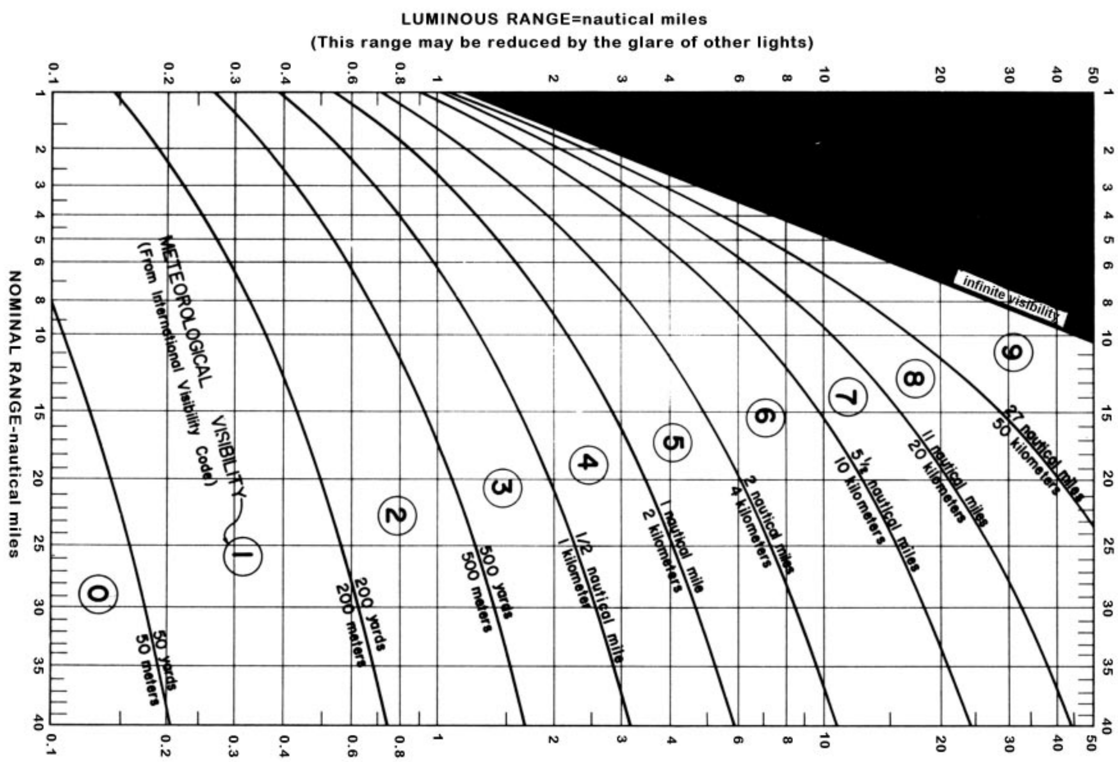


Figure 408a. Luminous Range Diagram.

rological visibility is 11 nautical miles, enter the Luminous Range Diagram with nominal range 15 nautical miles on the horizontal nominal range scale; follow a vertical line upward until it intersects the curve on the diagram representing a meteorological visibility of 11 nautical miles; from this point follow a horizontal line to the right until it intersects the vertical luminous range scale at 16 nautical miles. A similar procedure is followed to find the luminous range when the meteorological visibility is 1 nautical mile.

Answers: *(1) 16 nautical miles; (2) 3 nautical miles.*

A light's **geographic range** depends upon the height of both the light and the observer. Sum the observer's distance to the horizon based on his height of eye and the light's distance to the horizon based on its height to calculate a light's geographic range. See Figure 408c. This illustration uses a light 150 feet above the water. Table 12, Distance of the Horizon, yields a value of 14.3 nautical miles for a height of 150 feet. Within this range, the light, if powerful enough and atmospheric conditions permit, is visible regardless of the height of eye of the observer. Beyond 14.3 nautical miles, the geographic range depends upon the observer's height of eye. Thus, by the Distance of the Horizon table mentioned above, an observer with height of eye of 5 feet can see the light on his horizon if he is 2.6 miles beyond the horizon of the light. The geographic range of the light is therefore 16.9 miles. For a height of 30 feet the distance is 14.3 + 6.4 = 20.7 miles. If the height of eye is 70 feet, the geographic range is 14.3 + 9.8 = 24.1 miles. A height of eye of 15 feet is often assumed when tabulating lights' geographic ranges.

Code No.	Weather	Yards
0	Dense fog	Less than 50
1	Thick fog	50-200
2	Moderate fog	200-500
3	Light fog	500-1000
		Nautical Miles
4	Thin fog	1/2-1
5	Haze	1-2
6	Light Haze	2-5 1/2
7	Clear	5 1/2-11
8	Very Clear	11.0-27.0.
9	Exceptionally Clear	Over 27.0

From the International Visibility Code.

Figure 408b. Meteorlogical Optical Range Table.

To predict the bearing and range at which a vessel will initially sight a light first determine the light's geographic range. Compare the geographic range with the light's luminous range. The lesser of the two ranges is the range at which the light will first be sighted. Plot a visibility arc centered on the light and with a radius equal to the lesser of the geographic or luminous ranges. Extend the vessel's track until it intersects the visibility arc. The bearing from the intersection point to the light is the light's predicted bearing at first sighting.

If the extended track crosses the visibility arc at a small angle, a small lateral track error may result in large bearing and time prediction errors. This is particularly apparent if the vessel is farther from the light than predicted; the vessel may pass the light without sighting it. However, not sighting a light when predicted does not always indicate the vessel is farther from the light than expected. It could also mean that atmospheric conditions are affecting visibility.

Example 2: *The nominal range of a navigational light 120 feet above the chart datum is 20 nautical miles. The meteorological visibility is 27 nautical miles.*

Required: *The distance at which an observer at a height of eye of 50 feet can expect to see the light.*

Solution: *The maximum range at which the light may be seen is the lesser of the luminous or geographic ranges. At 120 feet the distance to the horizon, by table or formula, is 12.8 miles. Add 8.3 miles, the distance to the horizon for a height of eye of 50 feet to determine the geographic range. The geographic range, 21.1 miles, is less than the luminous range, 40 miles.*

Answer: *21 nautical miles. Because of various uncertainties, the range is rounded off to the nearest whole mile.*

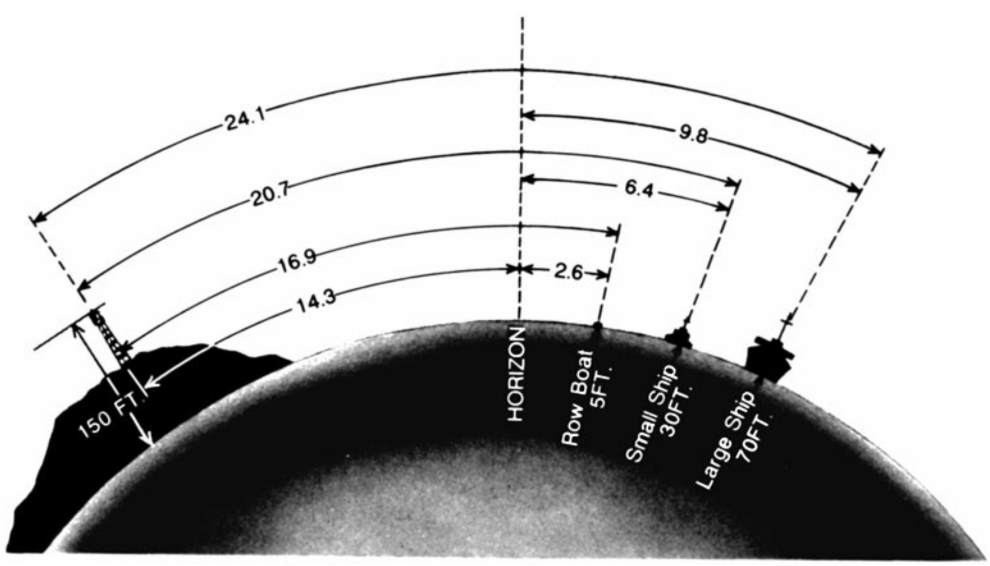


Figure 408c. Geographic Range of a light.

When first sighting a light, an observer can determine if it is on the horizon by immediately reducing his height of eye. If the light disappears and then reappears when the observer returns to his original height, the light is on the horizon. This process is called **bobbing a light**.

If a vessel has considerable vertical motion due to rough seas, a light sighted on the horizon may alternately appear and disappear. Wave tops may also obstruct the light periodically. This may cause the characteristic to appear different than expected. The light's true characteristics can be observed either by closing the range to the light or by the observer's increasing his height of eye.

If a light's range given in a foreign publication approximates the light's geographic range for a 15-foot observer's height of eye, assume that the printed range is the light's geographic range. Also assume that publication has listed the lesser of the geographic and nominal ranges. Therefore, if the light's listed range approximates the geographic range for an observer with a height of eye of 15 feet, then assume that the light's limiting range is the geographic range. Then, calculate the light's true geographic range using the actual observer's height of eye, not the assumed height of eye of 15 feet. This calculated true geographic range is the range at which the light will first be sighted.

Example 3: *The range of a light as printed on a foreign chart is 17 miles. The light is 120 feet above chart datum. The meteorological visibility is 10 nautical miles.*

Required: *The distance at which an observer at a height of eye of 50 feet can expect to see the light.*

Solution: *Calculate the geographic range of the light assuming a 15 foot observer's height of eye. At 120 feet the distance to the horizon is 12.8 miles. Add 4.5 miles (the distance to the horizon at a height of 15 feet) to 12.8 miles; this range is 17.3 miles. This approximates the range listed on the chart. Then assuming that the charted range is the geographic range for a 15-foot observer height of eye and that the nominal range is the greater than this charted range, the predicted range is found by calculating the true geographic range with a 50 foot height of eye for the observer.*

Answer: *The predicted range = 12.8 mi. + 8.3 mi. = 21.1 mi.. The distance in excess of the charted range depends on the luminous intensity of the light and the meteorological visibility.*

409. USCG *Light Lists*

The U.S. Coast Guard *Light List* (7 volumes) gives information on lighted navigation aids, unlighted buoys, radiobeacons, radio direction finder calibration stations, daybeacons, racons, and Loran stations.

Each volume of the *Light List* contains aids to navigation in geographic order from north to south along the Atlantic coast, from east to west along the Gulf coast, and from south to north along the Pacific coast. It lists seacoast aids first, followed by entrance and harbor aids listed from seaward. Intracoastal Waterway aids are listed last in geographic order in the direction from New Jersey to Florida to the Texas/Mexico border.

The listings are preceded by a description of the aids to navigation system in the United States, luminous range diagram, geographic range tables, and other information.

410. NIMA *List of Lights, Radio Aids, and Fog Signals*

The National Imagery and Mapping Agency publishes the *List of Lights, Radio Aids, and Fog Signals* (usually referred to as the *List of Lights,* not to be confused with the Coast Guard's *Light List*). In addition to information on lighted aids to navigation and sound signals in foreign waters, the NIMA *List of Lights* provides information on storm signals, signal stations, racons, radiobeacons, and radio direction finder calibration stations located at or near lights. For more details on radio navigational aids, consult *Pub. 117, Radio Navigational Aids.*

The NIMA *List of Lights* does not include information on lighted buoys inside harbors. It does include certain aeronautical lights situated near the coast; however, these lights are not designed for marine navigation and are subject to unreported changes.

Foreign notices to mariners are the main correctional information source for the NIMA *Lists of Lights*; other sources, such as ship reports, are also used. Many aids to navigation in less developed countries may not be well maintained. They are subject to damage by storms and vandalism, and repairs may be delayed for long periods.

MISCELLANEOUS NAUTICAL PUBLICATIONS

411. NIMA *Radio Navigational Aids (Pub. 117)*

This publication is a selected list of worldwide radio stations which perform services to the mariner. Topics covered include radio direction finder and radar stations, radio time signals, radio navigation warnings, distress and safety communications, medical advice via radio, long-range navigation aids, the AMVER system, and interim procedures for U.S. vessels in the event of an outbreak of hostilities. *Pub. 117* is corrected via the *Notice to Mariners* and is updated periodically with a new edition.

Though *Pub. 117* is essentially a list of radio stations providing vital maritime communication and navigation services, it also contains information which explains the capabilities and limitations of the various systems.

412. *Chart No. 1*

Chart No. 1 is not actually a chart but a book containing a key to chart symbols. Most countries which produce charts also produce such a list. The U.S. *Chart No. 1* contains a listing of chart symbols in four categories:

- Chart symbols used by the National Ocean Service
- Chart symbols used by the Defense Mapping Agency
- Chart symbols recommended by the International Hydrographic Organization
- Chart symbols used on foreign charts reproduced by NIMA

Subjects covered include general features of charts, topography, hydrography, and aids to navigation. There is also a complete index of abbreviations and an explanation of the IALA buoyage system.

413. NIMA *World Port Index (Pub. 150)*

The *World Port Index* contains a tabular listing of thousands of ports throughout the world, describing their locations, characteristics, facilities, and services available. Information is arranged geographically; the index is arranged alphabetically.

Coded information is presented in columns and rows. This information supplements information in the *Sailing Directions*. The applicable volume of *Sailing Directions* and the number of the harbor chart are given in the *World Port Index*. The *Notice to Mariners* corrects this book.

414. NIMA *Distances Between Ports (Pub. 151)*

This publication lists the distances between major ports. Reciprocal distances between two ports may differ due to different routes chosen because of currents and climatic conditions. To reduce the number of listings needed, junction points along major routes are used to consolidate routes converging from different directions.

This book can be most effectively used for voyage planning in conjunction with the proper volume(s) of the *Sailing Directions (Planning Guide)*. It is corrected via the *Notice to Mariners*.

415. NIMA *International Code Of Signals (Pub. 102)*

This book lists the signals to be employed by vessels at sea to communicate a variety of information relating to safety, distress, medical, and operational information. This publication became effective in 1969.

According to this code, each signal has a unique and complete meaning. The signals can be transmitted via Morse light and sound, flag, radio-telegraphy and -telephony, and semaphore. Since these methods of signaling are internationally recognized, differences in language between sender and receiver are immaterial; the message will be understood when decoded in the language of the receiver, regardless of the language of the sender. The *Notice to Mariners* corrects *Pub. 102*.

416. Almanacs

For celestial sight reduction, the navigator needs an **almanac** for ephemeris data. The *Nautical Almanac*, produced jointly by H.M. Nautical Almanac Office and the U.S. Naval Observatory, is the most common almanac used for celestial navigation. It also contains information on sunrise, sunset, moonrise, and moonset, as well as compact sight reduction tables. The *Nautical Almanac* is published annually.

The *Air Almanac* contains slightly less accurate ephemeris data for air navigation. It can be used for marine navigation if slightly reduced accuracy is acceptable.

Chapter 19 provides more detailed information on using the *Nautical Almanac*.

417. Sight Reduction Tables

Without a calculator or computer programmed for sight reduction, the navigator needs **sight reduction tables** to solve the celestial triangle. Two different sets of tables are commonly used at sea.

Sight Reduction Tables for Marine Navigation, Pub. 229, consists of six volumes of tables designed for use with the *Nautical Almanac* for solution of the celestial triangle by the **Marcq Saint Hilaire** or **intercept** method. The tabular data are the solutions of the navigational triangle of which two sides and the included angle are known and it is necessary to find the third side and adjacent angle.

Each volume of Pub. 229 includes two 8 degree zones, comprising 15 degree bands from 0 to 90 degrees, with a 1° degree overlap between volumes. Pub. 229 is a joint publication produced by the National Imagery and Mapping Agency, the U.S. Naval Observatory, and the Royal Greenwich Observatory.

Sight Reduction Tables for Air Navigation, Pub. 249, is also a joint production of the three organizations above. It is issued in three volumes. Volume 1 contains the values of the altitude and true azimuth of seven selected stars chosen to

provide, for any given position and time, the best observations. A new edition is issued every 5 years for the upcoming astronomical epoch. Volumes 2 (0° to 40°) and 3 (39° to 89°) provide for sights of the sun, moon, and planets.

418. Catalogs

A chart catalog is a valuable reference to the navigator for voyage planning, inventory control, and ordering. There are two major types of catalogs, one for the military and one for the civilian market.

The military navigator will see the NIMA nautical chart catalog as part of a larger suite of catalogs including aeronautical (Part 1), hydrographic (Part 2), and topographic (Part 3) products. Each Part consists of one or more volumes. Unclassified NIMA nautical charts are listed in Part 2, Volume 1. This is available only to U.S. military users, DoD contractors, and those who support them.

This catalog contains comprehensive ordering instructions and information about the products listed. Also listed are addresses of all Combat Support Center field offices, information on crisis support, and other special situations. The catalog is organized by geographic region corresponding to the chart regions 1 through 9. A special section of miscellaneous charts and publications is included. This section also lists products produced by NOS, the U.S. Army Corps of Engineers, U.S. Coast Guard, U.S. Naval Oceanographic Office, and some foreign publications from the United Kingdom and Canada.

The civilian navigator should refer to catalogs produced by the National Ocean Service. For U.S. waters, NOS charts are listed in a series of single sheet “charts” showing a major region of the U.S. with individual chart graphics shown. These catalogs also list charts showing titles and scales. Finally, it lists sales agents from whom the products may be purchased.

NIMA products for the civilian navigator are listed by NOS in a series of regionalized catalogs similar to Part 2 Volume 1. These catalogs are also available through authorized NOS chart agents.

MARITIME SAFETY INFORMATION

419. *Notice To Mariners*

The ***Notice to Mariners*** is published weekly by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), prepared jointly with the National Ocean Service (NOS) and the U.S. Coast Guard. It advises mariners of important matters affecting navigational safety, including new hydrographic information, changes in channels and aids to navigation, and other important data. The information in the *Notice to Mariners* is formatted to simplify the correction of paper charts, sailing directions, light lists, and other publications produced by NIMA, NOS, and the U.S. Coast Guard.

It is the responsibility of users to decide which of their charts and publications require correction. Suitable records of *Notice to Mariners* should be maintained to facilitate the updating of charts and publications prior to use.

Information for the *Notice to Mariners* is contributed by: the Defense Mapping Agency Hydrographic/Topographic Center (Department of Defense) for waters outside the territorial limits of the United States; National Ocean Service (National Oceanic and Atmospheric Administration, Department of Commerce), which is charged with surveying and charting the coasts and harbors of the United States and its territories; the U.S. Coast Guard (Department of Transportation) which is responsible for the safety of life at sea and the establishment and operation of aids to navigation; and the Army Corps of Engineers (Department of Defense), which is charged with the improvement of rivers and harbors of the United States. In addition, important contributions are made by foreign hydrographic offices and cooperating observers of all nationalities.

Over 60 countries which produce nautical charts also produce a notice to mariners. About one third of these are weekly, another third are bi-monthly or monthly, and the rest irregularly issued according to need. Much of the data in the U.S. *Notice to Mariners* is obtained from these foreign notices.

Correct U.S. charts with the U.S. *Notice to Mariners*. Similarly, correct foreign charts using the foreign notice because chart datums often vary according to region and geographic positions are not the same for different datums.

The *Notice* consists of a page of **Hydrograms** listing important items in the notice, a chart correction section organized by ascending chart number, a publications correction section, and a summary of broadcast navigation warnings and miscellaneous information.

Mariners are requested to cooperate in the correction of charts and publications by reporting all discrepancies between published information and conditions actually observed and by recommending appropriate improvements. A convenient reporting form is provided in the back of each *Notice to Mariners*.

Notice to Mariners No. 1 of each year contains important information on a variety of subjects which supplements information not usually found on charts and in navigational publications. This information is published as **Special Notice to Mariners Paragraphs**. Additional items considered

of interest to the mariner are also included in this *Notice*.

420. *Summary Of Corrections*

A close companion to the *Notice to Mariners* is the ***Summary of Corrections***. The *Summary* is published in five volumes. Each volume covers a major portion of the earth including several chart regions and many subregions. Volume 5 also includes special charts and publications corrected by the *Notice to Mariners*. Since the *Summaries* contain cumulative corrections, any chart, regardless of its print date, can be corrected with the proper volume of the *Summary* and all subsequent *Notice to Mariners*.

421. The Navigation Information Network

Most of the weekly *Notice to Mariners* production is computerized. This system is known as the **Automated Notice to Mariners System (ANMS)**. Design work on this system began in 1975, and the first *Notice* produced with it was issued in 1980. This system's software allows remote query via modem. This remote access system is known as the **Navigation Information Network (NAVINFONET)**.

Data available through NAVINFONET includes chart corrections,NIMA *List of Lights* corrections, Coast Guard *Light List* corrections, radio warnings, MARAD Advisories, NIMA hydrographic product catalog corrections, drill rig locations, ship hostile action report (SHAR) files, and GPS navigation system status reports. Messages can also be left for NIMA staff regarding suggestions, changes, corrections or comments on any navigation products.

The system does not have the capability to send graphics files, which prevents the transfer of chartlets. However, navigators can access most other significant information contained in the *Notice to Mariners*. Information is updated daily or weekly according to the *Notice to Mariners* production schedule. The system supports most internationally recognized telephone protocols and can presently transfer data at a maximum rate of 9600 baud.

NAVINFONET is not a replacement for the weekly *Notice to Mariners*, and in certain respects the accuracy of information cannot be verified by DMA. Certain files, for example, are entered directly into the data base without editing by NIMA staff. Also, drill rig locations are furnished by the companies which operate them. They are not required to provide these positions, and they cannot be verified. However, within these limitations, the system can provide information 2 to 3 weeks sooner than the printed *Notice to Mariners*, because the paper *Notice* must be compiled, edited, printed, and mailed after the digital version is completed.

NAVINFONET access is free, but the user must pay telephone charges. All users must register and receive a password by writing or calling NIMA, Attn.: MCC-NAVINFONET, Mail Stop D-44, 4600 Sangamore Rd., Bethesda, MD, 20816-5003; telephone (301) 227-3296.

The U.S. Coast and Geodetic Survey operates a similar free computerized marine information bulletin board containing a list of wrecks and obstructions, a nautical chart locator, a list of marine sediments samples, a datum conversion program for NAD 27 to NAD 83 datum conversions, and a list of aerial photographs available from NOAA. The modem phone number is (301) 713-4573, the voice line (301) 713-2653, and FAX (301) 713-4581. The address of the office is NOAA, NOS, C&GS, (N/CG211), 1315 East-West Highway, Silver Spring, MD, 20910

422. *Local Notice To Mariners*

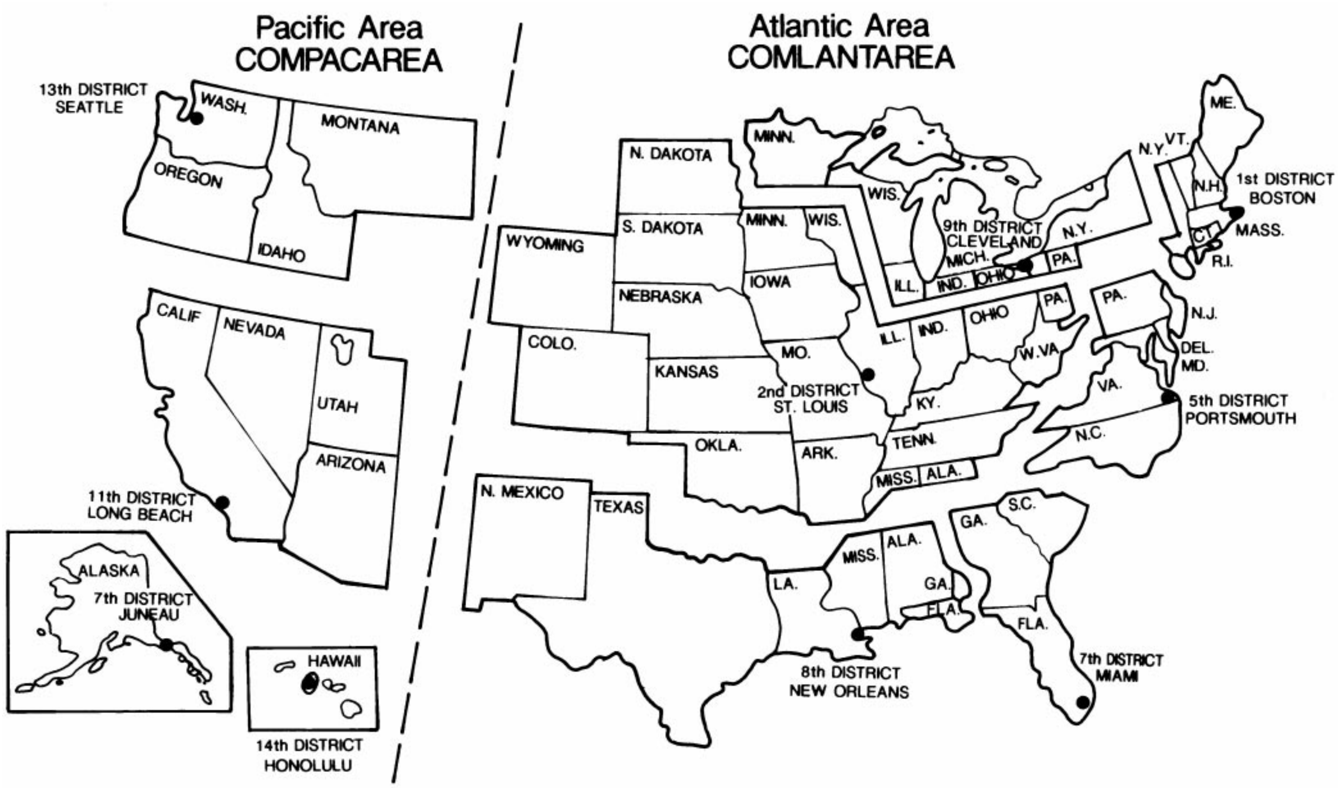
The ***Local Notice to Mariners*** is issued by each U.S. Coast Guard District to disseminate important information affecting navigational safety within that District. This *Notice* reports changes and deficiencies in aids to navigation maintained by the Coast Guard. Other marine information such as new charts, channel depths, naval operations, and regattas is included. Since temporary information of short duration is not included in the weekly *Notice to Mariners*, the *Local Notice to Mariners* may be the only source of such information. Small craft using the Intracoastal Waterway and small harbors not normally used by oceangoing vessels need it to keep charts and publications up-to-date. Since correcting information for U.S. charts in the NIMA *Notice* is obtained from the Coast Guard *Local Notices*, it is normal to expect a lag of 1 or 2 weeks for the NIMA *Notice* to publish a correction from this source.

The *Local Notice to Mariners* may be obtained free of charge by contacting the appropriate Coast Guard District Commander. Vessels operating in ports and waterways in several districts must obtain the *Local Notice to Mariners* from each district. See Figure 422 for a complete list of U.S. Coast Guard Districts.

423. Electronic Notice To Mariners

Electronic chart development is proceeding rapidly. The correction of these charts will become a major issue. In the near future, the quality standards of digital charts will permit the replacement of traditional paper charts. Neither paper nor electronic charts should be used unless corrected through the latest *Notice to Mariners*. Chapter 14 discusses potential methods for correcting electronic charts.

Until the electronic chart is recognized as being the legal equivalent of the paper chart, however, it cannot replace the paper chart on the bridge. Presently, therefore, the mariner must continue to use traditional paper charts. Their use, in turn, necessitates the continued use of the *Notice to Mariners* correction system.



COMMANDER, FIRST COAST GUARD DISTRICT
408 ATLANTIC AVENUE
BOSTON, MA 02110-3350
PHONE: DAY 617-223-8338, NIGHT 617-223-8558

COMMANDER, SECOND COAST GUARD DISTRICT
1222 SPRUCE STREET
ST. LOUIS, MO 63103-2832
PHONE: DAY 314-539-3714, NIGHT 314-539-3709

COMMANDER, FIFTH COAST GUARD DISTRICT
FEDERAL BUILDING
431 CRAWFORD STREET
PORTSMOUTH, VA 23704-5004
PHONE: DAY 804-398-6486, NIGHT 804-398-6231

COMMANDER, SEVENTH COAST GUARD DISTRICT
BRICKELL PLAZA FEDERAL BUILDING
909 SE 1ST AVENUE, RM: 406
MIAMI, FL 33131-3050
PHONE: DAY 305-536-5621, NIGHT 305-536-5611

COMMANDER GREATER ANTILLES SECTION
U.S. COAST GUARD
P.O. BOX S-2029
SAN JUAN, PR 00903-2029
PHONE: 809-729-6870

COMMANDER, EIGHTH COAST GUARD DISTRICT
HALE BOGGS FEDERAL BUILDING
501 MAGAZINE STREET
NEW ORLEANS, LA 70130-3396
PHONE: DAY 504-589-6234, NIGHT 504-589-6225

COMMANDER, NINTH COAST GUARD DISTRICT
1240 EAST 9TH STREET
CLEVELAND, OH 44199-2060
PHONE: DAY 216-522-3991, NIGHT 216-522-3984

COMMANDER, ELEVENTH COAST GUARD DISTRICT
FEDERAL BUILDING
501 W. OCEAN BLVD.
LONG BEACH, CA 90822-5399
PHONE: DAY 310-980-4300, NIGHT 310-980-4400

COMMANDER, THIRTEENTH COAST GUARD DISTRICT
FEDERAL BUILDING
915 SECOND AVENUE
SEATTLE, WA 98174-1067
PHONE: DAY 206-220-7280, NIGHT 206-220-7004

COMMANDER, FOURTEENTH COAST GUARD DISTRICT
PRINCE KALANIANAOLE FEDERAL BLDG.
9TH FLOOR, ROOM 9139
300 ALA MOANA BLVD.
HONOLULU, HI 96850-4982
PHONE: DAY 808-541-2317, NIGHT 808-541-2500

COMMANDER, SEVENTEENTH COAST GUARD DISTRICT
P.O. BOX 25517
JUNEAU, AK 99802-5517
PHONE: DAY 907-463-2245, NIGHT 907-463-2000

Figure 422. U.S. Coast Guard Districts.

CHAPTER 5

SHORT RANGE AIDS TO NAVIGATION

DEFINING SHORT RANGE AIDS TO NAVIGATION

500. Terms And Definitions

The term “short range aids to navigation” encompasses lighted and unlighted beacons, ranges, leading lights, buoys, and their associated sound signals. Each short range aid to navigation, commonly referred to as a NAVAID, fits within a system designed to warn the mariner of dangers and direct him toward safe water. An aid’s function determines its color, shape, light characteristic, and sound. This chapter explains the U.S. Aids to Navigation System as well as the international IALA Maritime Buoyage System.

The placement and maintenance of marine aids to navigation in U.S. waters is the responsibility of the United States Coast Guard. The Coast Guard maintains lighthouses, radiobeacons, racons, Loran C, sound signals, buoys, and daybeacons on the navigable waters of the United States, its territories, and possessions. Additionally, the Coast Guard exercises control over privately owned navigation aid systems.

A **beacon** is a stationary, visual navigation aid. Large lighthouses and small single-pile structures are both beacons. Lighted beacons are called **lights**; unlighted beacons are **daybeacons**. All beacons exhibit a **daymark** of some sort. In the case of a lighthouse, the color and type of structure are the daymarks. On small structures, these daymarks, consisting of colored geometric shapes called **dayboards**, often have lateral significance. Conversely, the markings on lighthouses and towers convey no lateral significance.

FIXED LIGHTS

501. Major And Minor Lights

Lights vary from tall, high intensity coastal lights to battery-powered lanterns on single wooden piles. Immovable, highly visible, and accurately charted, fixed lights provide navigators with an excellent source for bearings. The structures are often distinctively colored to aid in identification. See Figure 501a.

A **major light** is a high-intensity light exhibited from a fixed structure or a marine site. Major lights include primary seacoast lights and secondary lights. **Primary seacoast lights** are those major lights established for making landfall from sea and coastwise passages from headland to headland. **Secondary lights** are those major lights established at harbor entrances and other locations where high intensity and reliability are required.

A **minor light** usually displays a light of low to moderate intensity. Minor lights are established in harbors, along channels, rivers, and in isolated locations. They usually have numbering, coloring, and light and sound characteristics that are part of the lateral system of buoyage.

Lighthouses are placed where they will be of most use: on prominent headlands, at harbor and port entrances, on isolated dangers, or at other points where mariners can best use them to fix their position. The lighthouse’s principal purpose is to support a light at a considerable height above the water, thereby increasing its geographic range. Support equipment is often housed near the tower.

With few exceptions, all major lights are operated automatically. There are also many automatic lights on smaller structures maintained by the Coast Guard or other attendants. Unmanned major lights may have emergency generators and automatic monitoring equipment to increase the light’s reliability.

Light structures’ appearances vary. Lights in low-lying areas usually are supported by tall towers; conversely, light structures on high cliffs may be relatively short. However its support tower is constructed, almost all lights are similarly generated, focused, colored, and characterized.

Some major lights use modern rotating or flashing lights, but many older lights use **Fresnel** lenses. These lenses consist of intricately patterned pieces of glass in a heavy brass framework. Modern Fresnel-type lenses are cast from high-grade plastic; they are much smaller and lighter than their glass counterparts.

A **buoyant beacon** provides nearly the positional accuracy of a light in a place where a buoy would normally be used. See Figure 501b. The buoyant beacon consists of a heavy sinker to which a pipe structure is tightly moored. A buoyancy chamber near the surface supports the pipe. The light, radar reflector, and other devices are located atop the pipe above the surface of the water. The pipe with its buoyancy chamber tends to remain upright even in severe weather and heavy currents, providing a smaller watch circle than a buoy. The buoyant beacon is most useful along narrow ship channels in relatively sheltered water.

Figure 501a. Typical offshore light station.

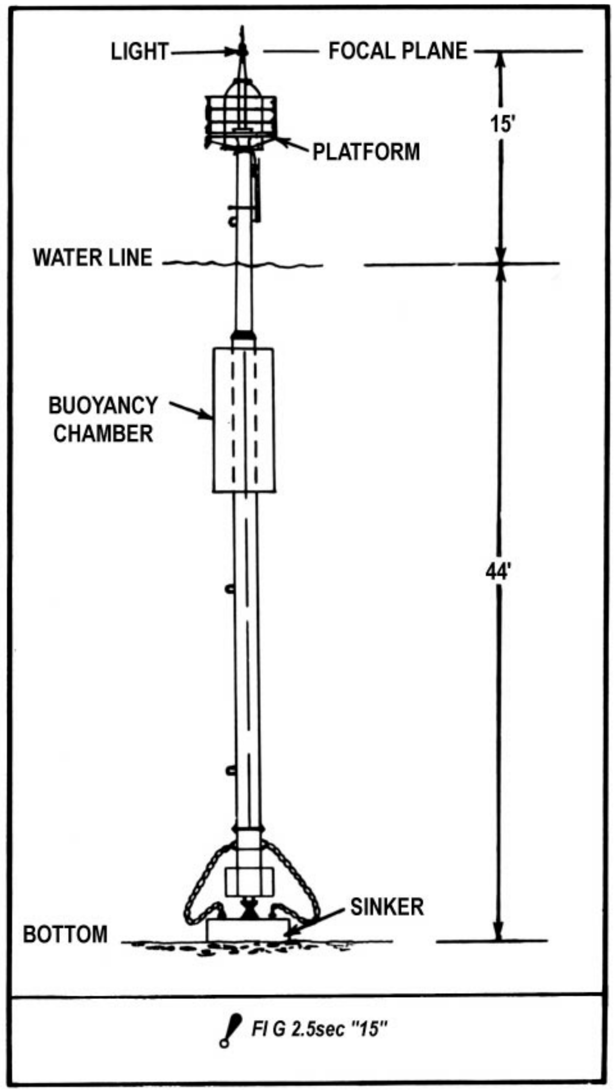


Figure 501b. Typical design for a buoyant beacon.

502. Range Lights

Range lights are light pairs that indicate a specific line of position when they are in line. The higher rear light is placed behind the front light. When the mariner sees the lights vertically in line, he is on the range line. If the front light appears left of the rear light, the observer is to the right of the rangeline; if the front appears to the right of the rear, the observer is left of the rangeline. Range lights are sometimes equipped with high intensity lights for daylight use. These are effective for long channels in hazy conditions when dayboards might not be seen. The range light structures are usually also equipped with dayboards for ordinary daytime use. Some smaller ranges, primarily in the Intracoastal Waterway and other inland waters, have just the dayboards with no lights. See Figure 502.

To enhance the visibility of range lights, the Coast Guard has developed 15-foot long lighted tubes called **light pipes**. They are mounted vertically, and the mariner sees them as vertical bars of light distinct from background lighting. Installation of light pipes is proceeding on several range markers throughout the country. The Coast Guard is also experimenting with long range sodium lights for areas requiring visibility greater than the light pipes can provide.

The output from a low pressure sodium light is almost entirely at one wavelength. This allows the use of an inexpensive band-pass filter to make the light visible even during the daytime. This arrangement eliminates the need for high intensity lights with their large power requirements.

Range lights are usually white, red, or green. They display various characteristics differentiating them from surrounding lights.

A **directional light** is a single light that projects a high intensity, special characteristic beam in a given direction. It is used in cases where a two-light range may not be practicable. A **directional sector light** is a directional light that emits two or more colored beams. The beams have a precisely oriented boundary between them. A normal application of a sector light would show three colored sections: red, white, and green. The white sector would indicate that the vessel is on the channel centerline; the

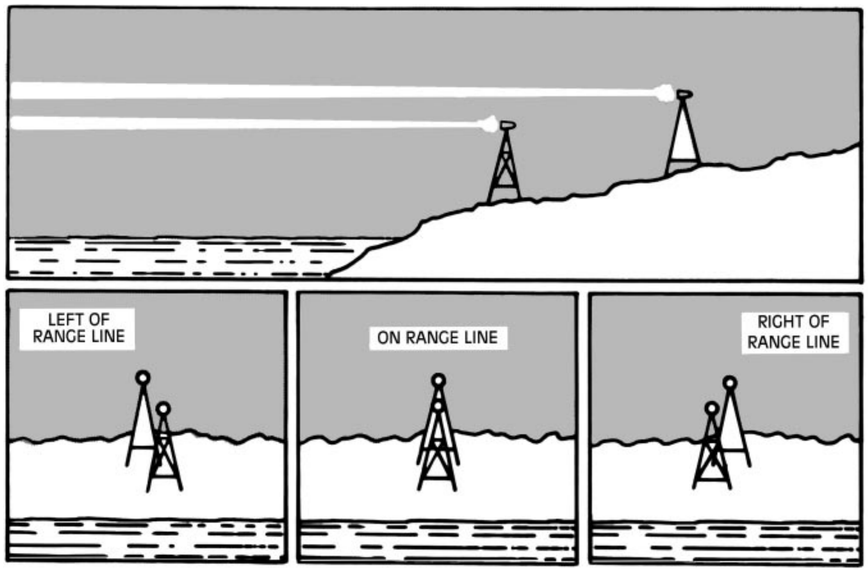


Figure 502. Range lights.

green sector would indicate that the vessel is off the channel centerline in the direction of deep water; and the red sector would indicate that the vessel is off the centerline in the direction of shoal water.

503. Aeronautical Lights

Aeronautical lights may be the first lights observed at night when approaching the coast. Those situated near the coast and visible from sea are listed in the *List of Lights*. These lights are not listed in the Coast Guard *Light List*. They usually flash alternating white and green.

Aeronautical lights are sequenced geographically in the *List of Lights* along with marine navigation lights. However, since they are not maintained for marine navigation, they are subject to changes of which maritime authorities may not be informed. These changes will be published in *Notice to Airmen* but perhaps not in *Notice To Mariners*.

504. Bridge Lights

Red, green, and white lights mark bridges across navigable waters of the United States. Red lights mark piers and other parts of the bridge. Red lights are also used on drawbridges to show when they are in the closed position. Green lights mark open drawbridges and mark the centerline of navigable channels through fixed bridges. The position will vary according to the type of structure. Navigational lights on bridges in the U.S. are prescribed by Coast Guard regulations.

Infrequently-used bridges may be unlighted. In foreign waters, the type and method of lighting may be different from those normally found in the United States. Drawbridges which must be opened to allow passage operate upon sound and light signals given by the vessel and acknowledged by the bridge. These required signals are detailed in the Code of Federal Regulations and the applicable Coast Pilot. Certain bridges may also be equipped with sound signals and radar reflectors.

505. Shore Lights

Shore lights usually have a shore-based power supply. Lights on pilings, such as those found in the Intracoastal Waterway, are battery powered. Solar panels may be installed to enhance the light's power supply. The lights consist of a power source, a flasher to determine the characteristic, a lamp changer to replace burned-out lamps, and a focusing lens.

Various types of rotating lights are in use. They do not have flashers but remain continuously lit while a lens or reflector rotates around the horizon.

The whole light system is carefully engineered to provide the maximum amount of light to the mariner for the least power use. Specially designed filaments and special grades of materials are used in the light to withstand the harsh marine environment.

The **flasher** electronically determines the characteristic by selectively interrupting the light's power supply according to the chosen cycle.

The **lamp changer** consists of several sockets arranged around a central hub. When the circuit is broken by a burned-out filament, a new lamp is rotated into position. Almost all lights have daylight switches which turn the light off at sunrise and on at dusk.

The **lens** for small lights may be one of several types. The common ones in use are omni-directional lenses of 155mm, 250mm, and 300mm. In addition, lights using parabolic mirrors or focused-beam lenses are used in leading lights and ranges. The lamp filaments must be carefully aligned with the plane of the lens or mirror to provide the maximum output of light. The lens' size is chosen according to the type of platform, power source, and lamp characteris-

tics. Additionally, environmental characteristics of the location are considered. Various types of light-condensing panels, reflex reflectors, or colored sector panels may be installed inside the lens to provide the proper characteristic.

A special heavy 200mm lantern is used in locations where ice and breaking water are a hazard.

LIGHT CHARACTERISTICS

506. Characteristics

A light has distinctive **characteristics** which distinguish it from other lights or convey specific information. A light may show a distinctive sequence of light and dark intervals. Additionally, a light may display a distinctive color or color sequence. In the Light Lists, the dark intervals are referred to as **eclipses**. An **occulting** light is a light totally eclipsed at regular intervals, the duration of light always being *greater* than the duration of darkness. A **flashing** light is a light which flashes at regular intervals, the duration of light always being *less* than the duration of darkness. An **isophase** light flashes at regular intervals, the duration of light being *equal* to the duration of darkness.

Light phase characteristics (Figure 506a and Figure 506b) are the distinctive sequences of light and dark intervals or sequences in the variations of the luminous intensity of a light. The light phase characteristics of lights which change color do not differ from those of lights which do not change color. A light showing different colors alternately is described as an **alternating** light. The alternating characteristic may be used with other light phase characteristics.

Light-sensitive switches extinguish most lighted navigation aids during daylight hours. However, owing to the various sensitivity of the light switches, all lights do not come on or go off at the same time. Mariners should account for this when identifying aids to navigation during twilight periods when some lighted aids are on while others are not.

507. Light Sectors

Sectors of colored glass or plastic are sometimes placed in the lanterns of certain lights to indicate dangerous waters. Lights so equipped show different colors when observed from different bearings. A sector changes the color of a light, but not its characteristic, when viewed from certain directions. For example, a four second flashing white light having a red sector will appear as a four second flashing red light when viewed from within the red sector.

Sectors may be only a few degrees in width or extend in a wide arc from deep water toward shore. Bearings referring to sectors are expressed in degrees true *as observed from a vessel*.

In most cases, areas covered by red sectors should be avoided. The nature of the danger can be determined from the chart. In some cases a narrow sector may mark the best water across a shoal, or a turning point in a channel.

Sectors generated by shadow-casting filters do not have precise boundaries as directional sector lights do. Therefore, the transition from one color to another is not abrupt. The colors change through an arc of uncertainty of 2° or greater, depending on the optical design of the light. Therefore determining bearings by observing the color change is less accurate than obtaining a bearing with an azimuth circle.

508. Factors Affecting Range And Characteristics

The condition of the atmosphere has a considerable effect upon a light's range. Sometimes lights are obscured by fog, haze, dust, smoke, or precipitation. On the other hand, refraction may cause a light to be seen farther than under ordinary circumstances. A light of low intensity will be easily obscured by unfavorable conditions of the atmosphere. For this reason, the intensity of a light should always be considered when looking for it in thick weather. Haze and distance may reduce the apparent duration of a light's flash. In some conditions of the atmosphere, white lights may have a reddish hue. In clear weather green lights may have a more whitish hue.

Lights placed at great elevations are more frequently obscured by clouds, mist, and fog than those near sea level. In regions where ice conditions prevail, an unattended light's lantern panes may become covered with ice or snow This may reduce the light's luminous range and change the light's observed color.

The distance from a light *cannot* be estimated by its apparent brightness. There are too many factors which can change the perceived intensity. Also, a powerful, distant light may sometimes be confused with a smaller, closer one with similar characteristics. Every light sighted should be carefully evaluated to determine if it is the one expected.

The presence of bright shore lights may make it difficult to distinguish navigational lights from background lighting. Lights may also be obscured by various shore obstructions, natural and man-made. The Coast Guard requests mariners to report these cases to the nearest Coast Guard station.

A light's **loom** is seen through haze or the reflection from low-lying clouds when the light is beyond its geographic range. Only the most powerful lights can generate a loom. The loom may sometimes be sufficiently defined to obtain a bearing. If not, an accurate bearing on a light beyond geographic range may sometimes be obtained by ascending to a higher level where the light can be seen, and noting a star directly over the light. The bearing of the star can then be obtained from the navigating bridge and the bearing to the light plotted indirectly.

At short distances, some of the brighter flashing lights may show a faint continuous light, or faint flashes, between

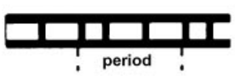
Illustration	Type Description	Abbreviation
	1. FIXED. A light showing continuously and steadily.	F
	2. OCCULTING. A light in which the total duration of light in a period is longer than the total duration of darkness and the intervals of darkness (eclopses) are usually of equal duration.	
	2.1 Single-occulting. An occulting light in which an eclipse is regularly repeated.	Oc
	2.2 Group-occulting. An occulting light in which a group of eclipses, specified in numbers, is regularly repeated.	Oc(2)
	2.3 Composite group-occulting. A light, similar to a group-occulting light, except that successive groups in a period have different numbers of eclipses.	Oc(2+1)
	3. ISOPHASE. A light in which all durations of light and darkness are equal.	Iso
	4. FLASHING. A flashing light in which the total duration of light in a period is shorter than the total duration of darkness and the appearances of light (flashes) are usually of equal duration.	
	4.1 Single-flashing. A flashing light in which a flash is regularly repeated (frequency not exceeding 30 flashes per minute).	Fl

Figure 506a. Light phase characteristics.

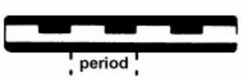
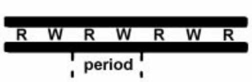
Illustration	Type Description	Abbreviation
	4.2 Group-flashing. A flashing light in which a group of glashes, specified in number, is regularly repeated.	Fl (2)
	4.3 Composite group-flashing. A light similar to a group flashing light except that successive groups in the period have different numbers of flashes.	Fl (2+1)
	5. QUICK. A light in which flashes are produced at a rate of 60 flashes per minute.	
	5.1 Contiuous quick. A quick light in which a flash is regulary repeated.	Q
	5.2 Interrupted quick. A quick light in which the sequence of flashes is interrupted by regulary repeated eclipses of constant and long duration.	IQ
	6. MORES CODE. A light in which the sequence of flashes is interrupted by regulary repeated eclipses of constant and long duration.	Mo (A)
	7. FIXED AND FLASHING. A quick light in which the sequence of flashes is interrupted by regulary repeated eclipses of constant and long duration.	FFl
	8. ALTERNATING. A light showing differenct colors alternately.	Al RW

Figure 506b. Light phase characteristics.

regular flashes. This is due to reflections of a rotating lens on panes of glass in the lighthouse.

If a light is not sighted within a reasonable time after prediction, a dangerous situation may exist. Conversely, the light may simply be obscured or extinguished. The ship's position should immediately be fixed by other means to determine any possibility of danger.

The apparent characteristic of a complex light may change with the distance of the observer. For example, a light with a characteristic of fixed white and alternating flashing white and red may initially show as a simple flashing white light. As the vessel draws nearer, the red flash will become visible and the characteristic will apparently be alternating flashing white and red. Later, the fainter fixed white light will be seen between the flashes and the true characteristic of the light finally recognized as fixed white, alternating flashing white and red (F W Al W R). This is because for a given candlepower, white is the most visible color, green less so, and red least of the three. This fact also accounts for the different ranges given in the Light Lists for some multi-color sector lights. The same lamp has different ranges according to the color imparted by the sector glass.

A light may be **extinguished** due to weather, battery failure, vandalism, or other causes. In the case of unattended lights, this condition might not be immediately corrected. The mariner should report this condition to the nearest Coast Guard station. During periods of armed conflict, certain lights may be deliberately extinguished without notice.

Offshore light stations should always be left well off the course whenever searoom permits.

BUOYS

509. Definitions And Types

Buoys are floating aids to navigation. They mark channels, indicate shoals and obstructions, and warn the mariner of dangers. Buoys are used where fixed aids would be uneconomical or impractical due to the depth of water. By their color, shape, topmark, number, and light characteristics, buoys indicate to the mariner how to avoid hazards and stay in safe water. The federal buoyage system in the U.S. is maintained by the Coast Guard.

There are many different sizes and types of buoys designed to meet a wide range of environmental conditions and user requirements. The size of a buoy is determined primarily by its location. In general, the smallest buoy which will stand up to local weather and current conditions is chosen.

There are five types of buoys maintained by the Coast Guard. They are:

1. Lateral marks.
2. Isolated danger marks.
3. Safe water marks.
4. Special marks.
5. Information/regulatory marks.

These conform in general to the specifications of the **International Association of Lighthouse Authorities (IALA)** buoyage system.

A **lighted buoy** is a floating hull with a tower on which a light is mounted. Batteries for the light are in watertight pockets in the buoy hull or in watertight boxes mounted on the buoy hull. To keep the buoy in an upright position, a counterweight is attached to the hull below the water surface. A radar reflector is built into the buoy tower.

The largest of the typical U.S. Coast Guard buoys can be moored in up to 190 feet of water, limited by the weight of chain the hull can support. The focal plane of the light is

Figure 509. Buoy showing counterweight.

15 to 20 feet high. The designed nominal visual range is 3.8 miles, and the radar range 4 miles. Actual conditions will cause these range figures to vary considerably.

The smallest buoys are designed for protected water. Some are made of plastic and weigh only 40 pounds. Specially designed buoys are used for fast current, ice, and other environmental conditions.

A variety of special purpose buoys are owned by other governmental organizations. Examples of these organizations include the Panama Canal Commission, the St. Lawrence Seaway Development Corporation, NOAA, and the Department of Defense. These buoys are usually navigational marks or data collection buoys with traditional round, boat-shaped, or discus-shaped hulls.

A special class of buoy, the **Ocean Data Acquisition System (ODAS)** buoy, is moored or floats free in offshore

waters. Positions are promulgated through radio warnings. These buoys are generally not large enough to cause damage in a collision, but should be given a wide berth regardless, as any loss would almost certainly result in the interruption of valuable scientific experiments. They are generally bright orange or yellow in color, with vertical stripes on moored buoys and horizontal bands on free-floating ones, and have a strobe light for night visibility.

Even in clear weather, the danger of collision with a buoy exists. If struck head-on, a large buoy can inflict severe damage to a large ship; it can sink a smaller one. Reduced visibility or heavy background lighting can contribute to the problem. The Coast Guard sometimes receives reports of buoys missing from station that were actually run down and sunk. Tugboats and towboats towing or pushing barges are particularly dangerous to buoys because of poor over-the-bow visibility when pushing or yawing during towing. The professional mariner must report *any* collision with a buoy to the nearest Coast Guard unit. Failure to do so may cause the next vessel to miss the channel or hit the obstruction marked by the buoy; it can also lead to fines and legal liability.

Routine on-station buoy maintenance consists of inspecting the mooring, cleaning the hull and superstructure, replacing the batteries, flasher, and lamps, checking wiring and venting systems, and verifying the buoy's exact position. Every few years, each buoy is replaced by a similar aid and returned to a Coast Guard maintenance facility for complete refurbishment.

The placement of a buoy depends on its purpose and its position on the chart. Most buoys are placed on charted position as accurately as conditions allow. However, if a buoy's purpose is to mark a shoal and the shoal is found to be in a different position than the chart shows, the buoy will be placed to properly mark the shoal, and not on its charted position.

510. Lights On Buoys

Buoy light systems consist of a **battery pack**, a **flasher** which determines the characteristic, a **lamp changer** which automatically replaces burned-out bulbs, a **lens** to focus the light, and a **housing** which supports the lens and protects the electrical equipment.

The **batteries** consist of 12-volt lead/acid type batteries electrically connected to provide sufficient power to run the proper flash characteristic and lamp size. These battery packs are contained in pockets in the buoy hull, accessible through water-tight bolted hatches or externally mounted boxes. Careful calculations based on light characteristics determine how much battery power to install.

The **flasher** determines the characteristic of the lamp. It is installed in the housing supporting the lens.

The **lamp changer** consists of several sockets arranged around a central hub. A new lamp rotates into position if the active one burns out.

Under normal conditions, the **lenses** used on buoys are 155mm in diameter at the base. 200 mm lenses are used where breaking waves or swells call for the larger lens. They are colored according to the charted characteristic of the buoy. As in shore lights, the lamp must be carefully focused so that the filament is directly in line with the focal plane of the lens. This ensures that the majority of the light produced is focused in a 360° horizontal fan beam A buoy light has a relatively narrow vertical profile. Because the buoy rocks in the sea, the focal plane may only be visible for fractions of a second at great ranges. A realistic range for sighting buoy lights is 4-6 miles in good visibility.

511. Sound Signals On Buoys

Lighted sound buoys have the same general configuration as lighted buoys but are equipped with either a bell, gong, whistle, or horn. **Bells** and **gongs** are sounded by tappers hanging from the tower that swing as the buoys roll in the sea. Bell buoys produce only one tone; gong buoys produce several tones. The tone-producing device is mounted between the legs of the pillar or tower.

Whistle buoys make a loud moaning sound caused by the rising and falling motions of the buoy in the sea. A sound buoy equipped with an electronic **horn** will produce a pure tone at regular intervals regardless of the sea state. Unlighted sound buoys have the same general appearance as lighted buoys, but their underwater shape is designed to make them lively in all sea states.

512. Buoy Moorings

Buoys require **moorings** to hold them in position. Typically the mooring consists of **chain** and a large concrete or cast iron **sinker**. See Figure 512. Because buoys are subjected to waves, wind, and tides, the moorings must be

Figure 512. A sinker used to anchor a buoy.

deployed with chain lengths much greater than the water depth. The scope of chain will normally be about 3 times the water depth. The length of the mooring chain defines a **watch circle** within which the buoy can be expected to swing. It is for this reason that the charted buoy symbol has a "position approximate" circle to indicate its charted position, whereas a light position is shown by a dot at the exact location. Actual watch circles do not necessarily coincide with the "position approximate" circles which represent them.

Over several years, the chain gradually wears out and must be replaced with new. The worn chain is often cast into the concrete of new sinkers.

513. Large Navigational Buoys

Large navigational buoys are moored in open water at approaches to major seacoast ports. These 40-foot diameter buoys (Figure 513) show lights from heights of about 36 feet above the water. Emergency lights automatically energize if the main light is extinguished. These buoys may also have a radiobeacon and sound signals. Their condition is monitored by radio from shore.

514. Wreck Buoys

A **wreck buoy** usually cannot be placed directly over the wreck it is intended to mark because the buoy tender may not want to pass over a shallow wreck or risk fouling the buoy mooring. For this reason, a wreck buoy is usually placed as closely as possible on the seaward or channelward side of a wreck. In some situations, two buoys may be used to mark the wreck, one lying off each end. The wreck may lie directly between them or inshore of a line between them, depending on the local situation. The *Local Notice To Mariners* should be consulted concerning details of the placement of wreck buoys on individual wrecks. Often it will also give particulars of the wreck and what activities may be in progress to clear it.

Figure 513. Large navigational buoy.

The charted position of a wreck buoy will usually be offset from the actual geographic position so that the wreck and buoy symbols do not coincide. Only on the largest scale chart will the actual and charted positions of both wreck and buoy be the same. Where they might overlap, it is the wreck symbol which occupies the exact charted position and the buoy symbol which is offset.

Wreck buoys are required to be placed by the owner of the wreck, but they may be placed by the Coast Guard if the owner is unable to comply with this requirement. In general, privately placed aids are not as reliable as Coast Guard aids.

Sunken wrecks are sometimes moved away from their buoys by storms, currents, freshets, or other causes. Just as shoals may shift away from the buoys placed to mark them, wrecks may shift away from wreck buoys.

515. Fallibility Of Buoys

Buoys cannot be relied on to maintain their charted positions consistently. They are subject to a variety of hazards including severe weather, collision, mooring casualties, and electrical failure. Report any discrepancy noted in a buoy to the U.S. Coast Guard.

The buoy symbol shown on charts indicates the approximate position of the sinker which secures the buoy to the seabed. The approximate position is used because of practical limitations in placing and keeping buoys and their sinkers in precise geographical locations. These limitations include prevailing atmospheric and sea conditions, the slope and type of material making up the seabed, the scope of the mooring chain, and the fact that the positions of the buoys and the sinkers are not under continuous surveillance. The position of the buoy shifts around the area shown by the chart symbol due to the forces of wind and current.

A buoy may not be in its charted position because of changes in the feature it marks. For example, a buoy meant to mark a shoal whose boundaries are shifting might frequently be moved to mark the shoal accurately. A *Local Notice To Mariners* will report the change, and a *Notice To Mariners* chart correction may also be written. In some small channels which change often, buoys are not charted even when considered permanent; local knowledge is advised in such areas.

For these reasons, a mariner must not rely completely upon the position or operation of buoys, but should navigate using bearings of charted features, structures, and aids to navigation on shore. Further, a vessel attempting to pass too close aboard a buoy risks a collision with the buoy or the obstruction it marks.

BUOYAGE SYSTEMS

516. Lateral And Cardinal Systems

There are two major types of buoyage systems: the **lateral system** and the **cardinal system**. The lateral system is best suited for well-defined channels. The description of each buoy indicates the direction of danger relative to the course which is normally followed. In principle, the positions of marks in the lateral system are determined by the **general direction** taken by the mariner when approaching port from seaward. These positions may also be determined with reference to the main stream of flood current. The United States Aids to Navigation System is a lateral system.

The cardinal system is best suited for coasts with numerous isolated rocks, shoals, and islands, and for dangers in the open sea. The characteristic of each buoy indicates the approximate true bearing of the danger it marks. Thus, an eastern quadrant buoy marks a danger which lies to the west of the buoy. The following pages diagram the cardinal and lateral buoyage systems as found outside the United States.

517. The IALA Maritime Buoyage System

Although most of the major maritime nations have used either the lateral or the cardinal system for many years, details such as the buoy shapes and colors have varied from country to country. With the increase in maritime commerce between countries, the need for a uniform system of buoyage became apparent.

In 1889, an International Marine Conference held in Washington, D.C., recommended that in the lateral system, starboard hand buoys be painted red and port hand buoys black. Unfortunately, when lights for buoys were introduced some years later, some European countries placed red lights on the black port hand buoys to conform with the red lights marking the port side of harbor entrances, while in North America red lights were placed on red starboard hand buoys. In 1936, a League of Nations subcommittee recommended a coloring system opposite to the 1889 proposal.

The **International Association of Lighthouse Authorities (IALA)** is a non-governmental organization which consists of representatives of the worldwide community of aids to navigation services to promote information exchange and recommend improvements based on new technologies. In 1980, with the assistance of IMO and the IHO, the lighthouse authorities from 50 countries and representatives of 9 international organizations concerned with aids to navigation met and adopted the **IALA Maritime Buoyage System**. They established two regions, **Region A** and **Region B**, for the entire world. Region A roughly corresponds to the 1936 League of Nations system, and Region B to the older 1889 system.

Lateral marks differ between Regions A and B. Lateral marks in Region A use red and green colors by day and night

to indicate port and starboard sides of channels, respectively. In Region B, these colors are reversed with red to starboard and green to port. In both systems, the conventional direction of buoyage is considered to be *returning from sea*, hence the phrase “red right returning” in IALA region B.

518. Types Of Marks

The **IALA Maritime Buoyage System** applies to all fixed and floating marks, other than lighthouses, sector lights, leading lights and daymarks, lightships and large navigational buoys, and indicates:

1. The side and center-lines of navigable channels.
2. Natural dangers, wrecks, and other obstructions.
3. Regulated navigation areas.
4. Other important features.

Most lighted and unlighted beacons other than leading marks are included in the system. In general, beacon topmarks will have the same shape and colors as those used on buoys. The system provides five types of marks which may be used in any combination:

1. Lateral marks indicate port and starboard sides of channels.
2. Cardinal marks, named according to the four points of the compass, indicate that the navigable water lies to the named side of the mark.
3. Isolated danger marks erected on, or moored directly on or over, dangers of limited extent.
4. Safe water marks, such as midchannel buoys.
5. Special marks, the purpose of which is apparent from reference to the chart or other nautical documents.

Characteristics Of Marks

The significance of a mark depends on one or more features:

1. By day—color, shape, and topmark.
2. By night—light color and phase characteristics.

Colors Of Marks

The colors red and green are reserved for lateral marks, and yellow for special marks. The other types of marks have black and yellow or black and red horizontal bands, or red and white vertical stripes.

Shapes Of Marks

There are five basic buoy shapes:

1. Can.
2. Cone.
3. Sphere.
4. Pillar.
5. Spar.

In the case of can, conical, and spherical, the shapes have lateral significance because the shape indicates the correct side to pass. With pillar and spar buoys, the shape has no special significance.

The term “pillar” is used to describe any buoy which is smaller than a “large navigation buoy (LNB)” and which has a tall, central structure on a broad base; it includes beacon buoys, high focal plane buoys, and others (except spar buoys) whose body shape does not indicate the correct side to pass.

Topmarks

The IALA System makes use of **can, conical, spherical,** and **X-shaped** topmarks only. Topmarks on pillar and spar buoys are particularly important and will be used wherever practicable, but ice or other severe conditions may occasionally prevent their use.

Colors Of Lights

Where marks are lighted, red and green lights are reserved for lateral marks, and yellow for special marks. The other types of marks have a white light, distinguished one from another by phase characteristic.

Phase Characteristics Of Lights

Red and green lights may have any phase characteristic, as the color alone is sufficient to show on which side they should be passed. Special marks, when lighted, have a yellow light with any phase characteristic not reserved for white lights of the system. The other types of marks have clearly specified phase characteristics of white light: various quick-flashing phase characteristics for cardinal marks, group flashing (2) for isolated danger marks, and relatively long periods of light for safe water marks.

Some shore lights specifically excluded from the IALA System may coincidentally have characteristics corresponding to those approved for use with the new marks. Care is needed to ensure that such lights are not misinterpreted.

519. IALA Lateral Marks

Lateral marks are generally used for well-defined channels; they indicate the port and starboard hand sides of the route to be followed, and are used in conjunction with a **conventional direction of buoyage**.

This direction is defined in one of two ways:

1. **Local direction of buoyage** is the direction taken by the mariner when approaching a harbor, river estuary, or other waterway from seaward.

2. **General direction of buoyage** is determined by the buoyage authorities, following a clockwise direction around continental land-masses, given in sailing directions, and, if necessary, indicated on charts by a large open arrow symbol.

In some places, particularly straits open at both ends, the local direction of buoyage may be overridden by the general direction.

Along the coasts of the United States, the characteristics assume that proceeding "from seaward" constitutes a clockwise direction: a southerly direction along the Atlantic coast, a westerly direction along the Gulf of Mexico coast, and a northerly direction along the Pacific coast. On the Great Lakes, a westerly and northerly direction is taken as being "from seaward" (except on Lake Michigan, where a southerly direction is used). On the Mississippi and Ohio Rivers and their tributaries, the characteristics of aids to navigation are determined as proceeding from sea toward the head of navigation. On the Intracoastal Waterway, proceeding in a generally southerly direction along the Atlantic coast, and in a generally westerly direction along the gulf coast, is considered as proceeding "from seaward."

520. IALA Cardinal Marks

A **cardinal mark** is used in conjunction with the compass to indicate where the mariner may find the best navigable water. It is placed in one of the four quadrants (north, east, south, and west), bounded by the true bearings NW-NE, NE-SE, SE-SW, and SW-NW, taken from the point of interest. A cardinal mark takes its name from the quadrant *in which it is placed*.

The mariner is safe if he passes north of a north mark, east of an east mark, south of a south mark, and west of a west mark.

A cardinal mark may be used to:

1. Indicate that the deepest water in an area is on the named side of the mark.
2. Indicate the safe side on which to pass a danger.
3. Emphasize a feature in a channel, such as a bend, junction, bifurcation, or end of a shoal.

Topmarks

Black double-cone topmarks are the most important feature, by day, of cardinal marks. The cones are vertically placed, one over the other. The arrangement of the cones is very logical: North is two cones with their points up (as in "north-up"). South is two cones, points down. East is two cones with bases together, and west is two cones with points together, which gives a wineglass shape. "West is a Wineglass" is a memory aid.

Cardinal marks carry topmarks whenever practicable, with the cones as large as possible and clearly separated.

Colors

Black and yellow horizontal bands are used to color a cardinal mark. The position of the black band, or bands, is related to the points of the black topmarks.

N	Points up	Black above yellow.
S	Points down	Black below yellow.
W	Points together	Black, yellow above and below.
E	Points apart	Yellow, black above and below.

Shape

The shape of a cardinal mark is not significant, but buoys must be pillars or spars.

Lights

When lighted, a cardinal mark exhibits a white light; its characteristics are based on a group of quick or very quick flashes which distinguish it as a cardinal mark and indicate its quadrant. The distinguishing quick or very quick flashes are:

North—Uninterrupted
East—three flashes in a group
South—six flashes in a group followed by a long flash
West—nine flashes in a group

As a memory aid, the number of flashes in each group can be associated with a clock face as follows:
(3 o'clock—E, 6 o'clock—S, and 9 o'clock—W).

The long flash (of not less than 2 seconds duration), immediately following the group of flashes of a south cardinal mark, is to ensure that its six flashes cannot be mistaken for three or nine.

The periods of the east, south, and west lights are, respectively, 10, 15, and 15 seconds if quick flashing; and 5, 10, and 10 seconds if very quick flashing.

Quick flashing lights flash at a rate between 50 and 79 flashes per minute, usually either 50 or 60. Very quick flashing lights flash at a rate between 80 and 159 flashes per minute, usually either 100 or 120.

It is necessary to have a choice of quick flashing or very quick flashing lights in order to avoid confusion if, for example, two north buoys are placed near enough to each other for one to be mistaken for the other.

521. IALA Isolated Danger Marks

An **isolated danger mark** is erected on, or moored on or above, an isolated danger of limited extent which has navigable water all around it. The extent of the surrounding navigable water is immaterial; such a mark can, for example, indicate either a shoal which is well offshore or an islet separated by a narrow channel from the coast.

Position

On a chart, the position of a danger is the center of the symbol or sounding indicating that danger; an isolated danger buoy may therefore be slightly displaced from its geographic position to avoid overprinting the two symbols. The smaller the scale, the greater this offset will be. At very large scales the symbol may be correctly charted.

Topmark

A black double-sphere topmark is, by day, the most important feature of an isolated danger mark. Whenever practicable, this topmark will be carried with the spheres as large as possible, disposed vertically, and clearly separated.

Color

Black with one or more red horizontal bands are the colors used for isolated danger marks.

Shape

The shape of an isolated danger mark is not significant, but a buoy will be a pillar or a spar.

Light

When lighted, a white flashing light showing a group of two flashes is used to denote an isolated danger mark. As a memory aid, associate two flashes with two balls in the topmark.

522. IALA Safe Water Marks

A **safe water mark** is used to indicate that there is navigable water all around the mark. Such a mark may be used as a center line, mid-channel, or landfall buoy.

Color

Red and white vertical stripes are used for safe water marks, and distinguish them from the black-banded, danger-marking marks.

Shape

Spherical, pillar, or spar buoys may be used as safe water marks.

Topmark

A single red spherical topmark will be carried, whenever practicable, by a pillar or spar buoy used as a safe water mark.

Lights

When lighted, safe water marks exhibit a white light. This light can be occulting, isophase, a single long flash, or Morse “A.” If a long flash (i.e. a flash of not less than 2 seconds) is used, the period of the light will be 10 seconds. As a memory aid, remember a single flash and a single sphere topmark.

523. IALA Special Marks

A **special mark** may be used to indicate a special area or feature which is apparent by referring to a chart, sailing directions, or notices to mariners. Uses include:

1. Ocean Data Acquisition System (ODAS) buoys.
2. Traffic separation marks.
3. Spoil ground marks.
4. Military exercise zone marks.
5. Cable or pipeline marks, including outfall pipes.
6. Recreation zone marks.

Another function of a special mark is to define a channel within a channel. For example, a channel for deep draft vessels in a wide estuary, where the limits of the channel for normal navigation are marked by red and green lateral buoys, may have its boundaries or centerline marked by yellow buoys of the appropriate lateral shapes.

Color

Yellow is the color used for special marks.

Shape

The shape of a special mark is optional, but must not conflict with that used for a lateral or a safe water mark. For example, an outfall buoy on the port hand side of a channel could be can-shaped but not conical.

Topmark

When a topmark is carried it takes the form of a single yellow X.

Lights

When a light is exhibited it is yellow. It may show any phase characteristic except those used for the white lights of cardinal, isolated danger, and safe water marks, In the case of ODAS buoys, the phase characteristic used is group-flashing with a group of five flashes every 20 seconds.

524. IALA New Dangers

A newly discovered hazard to navigation not yet shown

on charts, included in sailing directions, or announced by a *Notice To Mariners* is termed a **new danger**. The term covers naturally occurring and man-made obstructions.

Marking

A new danger is marked by one or more cardinal or lateral marks in accordance with the IALA system rules. If the danger is especially grave, at least one of the marks will be duplicated as soon as practicable by an identical mark until the danger has been sufficiently identified.

Lights

If a lighted mark is used for a new danger, it must exhibit a quick flashing or very quick flashing light. If a cardinal mark is used, it must exhibit a white light; if a lateral mark, a red or green light.

Racons

The duplicate mark may carry a Racon, Morse coded D, showing a signal length of 1 nautical mile on a radar display.

525. Chart Symbols And Abbreviations

Spar buoys and spindle buoys are represented by the same symbol; it is slanted to distinguish them from upright beacon symbols. The abbreviated description of the color of a buoy is given under the symbol. Where a buoy is colored in bands, the colors are indicated in sequence from the top. If the sequence of the bands is not known, or if the buoy is striped, the colors are indicated with the darker color first.

Topmarks

Topmark symbols are solid black except when the topmark is red.

Lights

The period of the light of a cardinal mark is determined by its quadrant and its flash characteristic (either quick-flashing or a very quick-flashing). The light's period is less important than its phase characteristic. Where space on charts is limited, the period may be omitted.

Light flares

Magenta light-flares are normally slanted and inserted with their points adjacent to the position circles at the base of the symbols so the flare symbols do not obscure the topmark symbols.

Radar Reflectors

Radar reflectors are not affected by the IALA buoyage rules. They are not charted for several reasons. It can be assumed that most major buoys are fitted with radar reflectors. It is also necessary to reduce the size and complexity of buoy symbols and associated legends. Finally, it is understood that, in the case of cardinal buoys, buoyage authorities site the reflector so that it cannot be mistaken for a topmark. For these reasons, radar reflectors are not charted under IALA rules.

The symbols and abbreviations of the IALA Maritime Buoyage System may be found in U.S.. Chart No. 1, Nautical Chart Symbols and Abbreviations, and in foreign equivalents.

526. Description Of The U.S. Aids to Navigation System

In the United States, the U.S. Coast Guard has incorporated the major features of the IALA system with the existing infrastructure of buoys and lights as explained below.

Colors

Under this system, green buoys mark a channel's port side and obstructions which must be passed by keeping the buoy on the port hand. Red buoys mark a channel's starboard side and obstructions which must be passed by keeping the buoy on the starboard hand.

Red and green horizontally banded **preferred channel buoys** mark junctions or bifurcations in a channel or obstructions which may be passed on either side. If the topmost band is green, the preferred channel will be followed by keeping the buoy on the port hand. If the topmost band is red, the preferred channel will be followed by keeping the buoy on the starboard hand.

Red and white vertically striped safe water buoys mark a fairway or mid-channel.

Reflective material is placed on buoys to assist in their detection at night with a searchlight. The color of the reflective material agrees with the buoy color. Red or green reflective material may be placed on preferred channel (junction) buoys; red if topmost band is red or green if the topmost band is green. White reflective material is used on safe water buoys. Special purpose buoys display yellow reflective material. Warning or regulatory buoys display orange reflective horizontal bands and a warning symbol. Intracoastal Waterway buoys display a yellow reflective square, triangle, or horizontal strip along with the reflective material coincident with the buoy's function.

Shapes

Certain unlighted buoys are differentiated by shape. Red buoys and red and green horizontally banded buoys with the topmost band red are cone-shaped buoys called **nuns**. Green buoys and green and red horizontally banded buoys with the topmost band green are cylinder-shaped buoys called **cans**.

Unlighted red and white vertically striped buoys may be pillar shaped or spherical. Lighted buoys, sound buoys, and spar

buoys are not differentiated by shape to indicate the side on which they should be passed. Their purpose is indicated not by shape but by the color, number, or light characteristics.

Numbers

All solid colored buoys are numbered, red buoys bearing even numbers and green buoys bearing odd numbers. (Note that this same rule applies in IALA System A also.) The numbers increase from seaward upstream or toward land. No other colored buoys are numbered; however, any buoy may have a letter for identification.

Light colors

Red lights are used only on red buoys or red and green horizontally banded buoys with the topmost band red. Green lights are used only on the green buoys or green and red horizontally banded buoys with the topmost band green. White lights are used on both "safe water" aids showing a Morse A characteristic and on Information and Regulatory aids.

Light Characteristics

Lights on red buoys or green buoys, if not occulting or isophase, will generally be regularly flashing (Fl). For ordinary purposes, the frequency of flashes will be not more than 50 flashes per minute. Lights with a distinct cautionary significance, such as at sharp turns or marking dangerous obstructions, will flash not less than 50 flashes but not more than 80 flashes per minute (quick flashing, Q). Lights on preferred channel buoys will show a series of grouped flashes with successive groups in a period having different number of flashes—composite group flashing (or a quick light in which the sequence of flashes is interrupted by regularly repeated eclipses of constant and long duration). Lights on safe water buoys will always show a white Morse Code "A" (Short-Long) flash recurring at the rate of approximately eight times per minute.

Daylight Controls

Lighted buoys have a special device to energize the light when darkness falls and to de-energize the light when day breaks. These devices are not of equal sensitivity; therefore all lights do not come on or go off at the same time. Mariners should ensure correct identification of aids during twilight periods when some light aids to navigation are on while others are not.

Special Purpose Buoys

Buoys for special purposes are colored yellow. White buoys with orange bands are for information or regulatory purposes. The shape of special purpose buoys has no significance. They are not numbered, but they may be lettered. If lighted, special purpose buoys display a yellow light usually with fixed or slow flash characteristics. Information and regulatory buoys, if lighted, display white lights.

BEACONS

527. Definition And Description

Beacons are fixed aids to navigation placed on shore or on pilings in relatively shallow water. If unlighted, the beacon is referred to as a **daybeacon**. A daybeacon is identified by its color and the color, shape, and number of its **dayboard**. The simplest form of daybeacon consists of a single pile with a dayboard affixed at or near its top. See Figure 527. Daybeacons may be used to form an unlighted range.

Dayboards identify aids to navigation against daylight backgrounds. The size of the dayboard required to make the aid conspicuous depends upon the aid's intended range.

Most dayboards also display numbers or letters for identification. The numbers, letters, and borders of most dayboards have reflective tape to make them visible at night.

The detection, recognition, and identification distances vary widely for any particular dayboard. They depend upon the luminance of the dayboard, the sun's position, and the local visibility conditions.

Figure 527. Daybeacon.

SOUND SIGNALS

528. Types Of Sound Signals

Most lighthouses and offshore light platforms, as well as some minor light structures and buoys, are equipped with sound-producing devices to help the mariner in periods of low visibility. Charts and Light Lists contain the information required for positive identification. Buoys fitted with bells, gongs, or whistles actuated by wave motion may produce no sound when the sea is calm. Sound signals are not designed to identify the buoy or beacon for navigation purposes. Rather, they allow the mariner to pass clear of the buoy or beacon during low visibility.

Sound signals vary. The navigator must use the Light List to determine the exact length of each blast and silent interval. The various types of sound signals also differ in tone, facilitating recognition of the respective stations.

Diaphones produce sound with a slotted piston moved back and forth by compressed air. Blasts may consist of a high and low tone. These alternate-pitch signals are called “two-tone.” Diaphones are not used by the Coast Guard, but the mariner may find them on some private navigation aids.

Horns produce sound by means of a disc diaphragm operated pneumatically or electrically. Duplex or triplex horn units of differing pitch produce a chime signal.

Sirens produce sound with either a disc or a cup-shaped rotor actuated electrically or pneumatically. Sirens are not used on U.S. navigation aids.

Whistles use compressed air emitted through a circumferential slot into a cylindrical bell chamber.

Bells and gongs are sounded with a mechanically operated hammer.

529. Limitations Of Sound Signals

As aids to navigation, sound signals have serious limitations because sound travels through the air in an unpredictable manner.

It has been clearly established that:

1. Sound signals are heard at greatly varying distances and that the distance at which a sound signal can be heard may vary with the bearing and timing of the signal.
2. Under certain atmospheric conditions, when a sound signal has a combination high and low tone, it is not unusual for one of the tones to be inaudible. In the case of sirens, which produce a varying tone, portions of the signal may not be heard.
3. When the sound is screened by an obstruction, there are areas where it is inaudible.
4. Operators may not activate a remotely controlled sound aid for a condition unobserved from the controlling station.
5. Some sound signals cannot be immediately started.
6. The status of the vessel’s engines and the location of the observer both affect the effective range of the aid.

These considerations justify the utmost caution when navigating near land in a fog. A navigator can never rely on sound signals alone; he should continuously man both the radar and fathometer. He should place lookouts in positions where the noises in the ship are least likely to interfere with hearing a sound signal. The aid upon which a sound signal rests is usually a good radar target, but collision with the aid or the danger it marks is always a possibility.

Emergency signals are sounded at some of the light and fog signal stations when the main and stand-by sound signals are inoperative. Some of these emergency sound signals are of a different type and characteristic than the main sound signal. The characteristics of the emergency sound signals are listed in the Light List.

The mariner should never assume:

1. That he is out of ordinary hearing distance because he fails to hear the sound signal.
2. That because he hears a sound signal faintly, he is far from it.
3. That because he hears it clearly, he is near it.
4. That the distance from and the intensity of a sound on any one occasion is a guide for any future occasion.
5. That the sound signal is not sounding because he does not hear it, even when in close proximity.
6. That the sound signal is in the direction the sound appears to come from.

MISCELLANEOUS U.S. SYSTEMS

530. Intracoastal Waterway Aids To Navigation

The Intracoastal Waterway (ICW) runs parallel to the Atlantic and Gulf of Mexico coasts from Manasquan Inlet on the New Jersey shore to the Texas/Mexican border. It follows rivers, sloughs, estuaries, tidal channels, and other natural waterways, connected with dredged channels where necessary. Some of the aids marking these waters are marked with yellow; otherwise, the marking of buoys and beacons follows the same system as that in other U.S. waterways.

Yellow symbols indicate that an aid marks the Intracoastal Waterway. Yellow triangles indicate starboard hand aids, and yellow squares indicate port hand aids when following the ICW's conventional direction of buoyage. Non-lateral aids such as safe water, isolated danger, and front range boards are marked with a horizontal yellow band. Rear range boards do not display the yellow band. At a junction with a federally-maintained waterway, the preferred channel mark will display a yellow triangle or square as appropriate. Junctions between the ICW and privately maintained waterways are not marked with preferred channel buoys.

531. Western Rivers System

Aids to navigation on the Mississippi River and its tributaries above Baton Rouge generally conform to the lateral system of buoyage in use in the rest of the U.S. The following differences are significant:

1. Buoys are not numbered.
2. The numbers on lights and daybeacons do not have lateral significance; they indicate the mileage from a designated point, normally the river mouth.
3. Flashing lights on the left side proceeding upstream show single green or white flashes while those on the right side show group flashing red or white flashes.
4. Diamond shaped crossing daymarks are used to indicate where the channel crosses from one side of the river to the other.

532. The Uniform State Waterway Marking System (USWMS)

This system was developed jointly by the U.S. Coast Guard and state boating administrators to assist the small craft operator in those state waters marked by participating states. The **USWMS** consists of two categories of aids to navigation. The first is a system of aids to navigation, generally compatible with the Federal lateral system of buoyage, supplementing the federal system in state waters. The other is a system of regulatory markers to warn small craft operator of dangers or to provide general information.

On a well-defined channel, red and black buoys are established in pairs called **gates**; the channel lies between the buoys. The buoy which marks the left side of the channel viewed looking upstream or toward the head of navigation is black; the buoy which marks the right side of the channel is red.

In an irregularly-defined channel, buoys may be staggered on alternate sides of the channel, but they are spaced at sufficiently close intervals to mark clearly the channel lying between them.

When there is no well-defined channel or when a body of water is obstructed by objects whose nature or location is such that the obstruction can be approached by a vessel from more than one direction, aids to navigation having cardinal significance may be used. The aids conforming to the cardinal system consist of three distinctly colored buoys.

1. A white buoy with a red top must be passed to the south or west of the buoy.
2. A white buoy with a black top must be passed to the north or east of the buoy.
3. A buoy showing alternate vertical red and white stripes indicates that an obstruction to navigation extends from the nearest shore to the buoy and that he must not pass between the buoy and the nearest shore.

The shape of buoys has no significance under the USWMS.

Regulatory buoys are colored white with orange horizontal bands completely around them. One band is at the top of the buoy and a second band just above the waterline of the buoy so that both orange bands are clearly visible.

Geometric shapes colored orange are placed on the white portion of the buoy body. The authorized geometric shapes and meanings associated with them are as follows:

1. A vertical open faced diamond shape means danger.
2. A vertical open faced diamond shape with a cross centered in the diamond means that vessels are excluded from the marked area.
3. A circular shape means that vessels in the marked area are subject to certain operating restrictions.
4. A square or rectangular shape indicates that directions or information is written inside the shape.

Regulatory markers consist of square and rectangular shaped signs displayed from fixed structures. Each sign is white with an orange border. Geometric shapes with the same meanings as those displayed on buoys are centered on the sign boards. The geometric shape displayed on a regulatory marker tells the mariner if he should stay well clear of the marker or if he may approach the marker in order to read directions.

533. Private Aids To Navigation

A **private navigation aid** is any aid established and maintained by entities other than the Coast Guard.

The Coast Guard must approve the placement of private navigation aids. In addition, the District Engineer, U.S. Army Corps of Engineers, must approve the placement of any structure, including aids to navigation, in the navigable waters of the U.S.

Private aids to navigation are similar to the aids established and maintained by the U.S. Coast Guard; they are

specially designated on the chart and in the Light List. In some cases, particularly on large commercial structures, the aids are the same type of equipment used by the Coast Guard. Although the Coast Guard periodically inspects some private navigation aids, the mariner should exercise special caution when using them.

In addition to private aids to navigation, numerous types of construction and anchor buoys are used in various oil drilling operations and marine construction. These buoys are not charted, as they are temporary, and may not be lighted well or at all. Mariners should give a wide berth to drilling and construction sites to avoid the possibility of fouling moorings. This is a particular danger in offshore oil fields, where large anchors are often used to stabilize the positions of drill rigs in deep water. Up to eight anchors may be placed at various positions as much as a mile from the drill ship. These may or may not be marked by buoys.

534. Protection By Law

It is unlawful to impair the usefulness of any navigation aid established and maintained by the United States. If any vessel collides with an navigation aid, it is the legal duty of the person in charge of the vessel to report the accident to the nearest U.S. Coast Guard station.

CHAPTER 6

MAGNETIC COMPASS ADJUSTMENT

GENERAL PROCEDURES FOR MAGNETIC COMPASS ADJUSTMENT

600. Introduction

This chapter presents information and procedures for magnetic compass adjustment. Sections 601 and 613 cover procedures designed to eliminate compass errors satisfactorily. Refer to Figure 607 for condensed information regarding the various compass errors and their correction.

The term **compass adjustment** refers to any change of permanent magnet or soft iron correctors to reduce normal compass errors. The term **compass compensation** refers to any change in the current slupplied to the compass compensating coils to reduce degaussing errors.

601. Adjustment Check-Off List

If the magnetic adjustment necessitates (a) movement of degaussing compensating coils, or (b) a change of Flinders bar length, check also the coil compensation per section 646.

Expeditious compass adjustment depends on the application of the various correctors in an optimum sequence designed to minimize the number of correction steps. Certain adjustments may be made conveniently at dockside, simplifying the at sea adjustment procedures.

Moving the wrong corrector wastes time and upsets all previous adjustments, so be careful to make the correct adjustments. Throughout an adjustment, special care should be taken to pair off spare magnets so that the resultant field about them will be negligible. To make doubly sure that the compass is not affected by a spare magnet's stray field, keep them at an appropriate distance until they are actually inserted into the binnacle.

A. Dockside tests and adjustments.

1. Physical checks on the compass and binnacle.
    a. Remove any bubbles in compass bowl (section 610).
    b. Test for moment and sensibility of compass needles (section 610).
    c. Remove any slack in gimbal arrangement.
    d. Magnetization check of spheres and Flinders bar (section 610).
    e. Alignment of compass with fore-and-aft line of ship (section 610).
    f. Alignment of magnets in binnacle.
    g. Alignment of heeling magnet tube under pivot point of compass.
    h. See that corrector magnets are available.

2. Physical checks of gyro, azimuth circle, and peloruses.
    a. Alignment of peloruses with fore-and-aft line of ship (section 610).
    b. Synchronize gyro repeaters with master gyro.
    c. Ensure azimuth circles and peloruses are in good condition.

3. Necessary data.
    a. Past history or log data which might establish length of Flinders bar (sections 610 and 623).
    b. Azimuths for date and observer's position (section 633 and Chapter 17).
    c. Ranges or distant objects in vicinity if needed (local charts).
    d. Correct variation (local charts).
    e. Degaussing coil current settings for swing for residual deviations after adjustment and compensation (ship's Degaussing Folder).

4. Precautions.
    a. Determine transient deviations of compass from gyro repeaters, doors, guns, etc. (sections 636 and 639).
    b. Secure all effective magnetic gear in normal seagoing position before beginning adjustments.
    c. Make sure degaussing coils are secured before beginning adjustments. Use reversal sequence, if necessary.
    d. Whenever possible, correctors should be placed symmetrically with respect to the compass.

5. Adjustments.
    a. Place Flinders bar according to best available information (sections 610, 622 through 625).
    b. Set spheres at mid-position, or as indicated by last deviation table.
    c. Adjust heeling magnet, using balanced dip needle if available (section 637).

B. Adjustments at sea. Make these adjustments with the ship on an even keel and steady on each heading. When

Fore-and-aft and athwartship magnets			Quadrantial spheres			Flinders bar		
Deviation → **Magnets** ↓	Easterly on east *and* westerly on west. (+B error)	Westerly on east *and* easterly on west. (-B error)	**Deviation** → **Spheres** ↓	E. on NE, E. on SE, W. on SW, and W. on NW. (+D error)	W. on NE, E. on SE, W. on SW, andE. on NW. (-D error)	**Deviation change with latitude change** → **Bar** ↓	E. on E. and W. on W when sailing toward equator from north latitude or away from equator to south latitude.	W. on E. and E. on W when sailing toward equator from north latitude or away from equator to south latitude.
No fore and aft magnets in binnacle.	Place magnets red forward.	Place magnets red aft.	No spheres on binnacle.	Place spheres athwartship.	Place spheres fore and aft.	No bar in holder.	Place required of bar forward.	Place required amount of bar aft.
Fore and aft magnets red forward.	Raise magnets.	Lower magnets.	Spheres at athwartship position.	Move spheres toward compass or use larger spheres.	Move spheres outwards or remove.	Bar forward of binnacle.	Increase amount of bar forward.	Deacrease amount of bar forward.
Fore and aft magnets red aft.	Lower magnets.	Raise magnets.	Spheres at fore and aft position.	Move spheres outward or remove.	Move spheres toward compass or use larger spheres.	Bar aft of binnacle.	Decrease amount of bar aft.	Increase amount of bar aft.
Deviation → **Magnets** ↓	Easterly on north and westerly on south. (+C error)	Westerly on north and easterly on south. (-C error)	**Deviation** → **Spheres** ↓	E. on N, W. on E, E. on S, *and* W. on W. (+E error)	W. on N, E. on E, W. on S, *and* E. on W. (-E error)	↑ **Bar** **Deviation change with latitude change** →	W. on E. and E. on W. when sailing toward equator from south latitude or away from equator to north latitude.	E. on E. and W. on W. when sailing toward equator from south latitude or away from equator to south latitude
No athwartship magnets in binnacle.	Place athwartship magnets red starboard.	Place athwartship magnets red port.	No spheres on binnacle.	Place spheres at port forward and starboard aft intercardinal positions.	Place spheres at starboard foreward and port aft intercardinal positions.	Heeling magnet (Adjust with changes in magnetic latitude) If compass north is attracted to high side of ship when rolling, raise the heeling magnet if red end is up and *lower* the heeling magnet if blue end is up.		
Athwartship magnets red starboard.	Raise magnets.	Lower magnets.	Spheres at athwartship position.	Slew spheres clockwise through required angle.	Slew spheres counter-clockwise through required angle.	If compass north is attracted to low side of ship when rolling, *lower* the heeling magnet if red end is up and *raise* the heeling magnet if blue end is up. NOTE: Any change in placement of the heeling magnet will affect the deviations on all headings.		
Athwartship magnets red port.	Lower magnets.	Raise magnets.	Spheres at fore and aft position.	Slew spheres counter-clockwise through required angle.	Slew spheres clockwise through required angle.			

Figure 601. Mechanics of magnetic compass adjustment.

using the gyro, swing slowly from heading to heading and check gyro error by sun's azimuth or ranges on each heading to ensure a greater degree of accuracy (section 631). Be sure gyro is set for the mean speed and latitude of the vessel. Note all precautions in section A-4 above. Fly the "OSCAR QUEBEC" international code signal to indicate such work is in progress. Section 631 discusses methods for placing the ship on desired headings.

1. Adjust the heeling magnet while the ship is rolling on north and south magnetic headings until the oscillations of the compass card have been reduced to an average minimum. This step is not required if prior adjustment has been made using a dip needle to indicate proper placement of the heeling magnet.
2. Come to a cardinal magnetic heading, e.g., east (090°). Insert fore-and-aft B magnets, or move the existing B magnets, to remove *all* deviation.
3. Come to a south (180°) magnetic heading. Insert athwartship C magnets, or move the existing C magnets, to remove *all* deviation.
4. Come to a west (270°) magnetic heading. Correct *half* of any observed deviation by moving the B magnets.
5. Come to a north (000°) magnetic heading. Correct *half* of any observed deviation by moving the C magnets.

The cardinal heading adjustments should now be complete.

6. Come to any intercardinal magnetic heading, e.g., northeast (045°). Correct any observed deviation by moving the spheres in or out.
7. Come to the next intercardinal magnetic heading, e.g., southeast (135°). Correct *half* of any observed deviation by moving the spheres.

The intercardinal heading adjustments should now be complete, although more accurate results might be obtained by correcting the D error determined from the deviations on all four intercardinal headings, as discussed in section 615.

8. Secure all correctors before swinging for residual deviations.
9. Swing for residual undegaussed deviations on as many headings as desired, although the eight cardinal and intercardinal headings should be sufficient.
10. Should there still be any large deviations, analyze the deviation curve to determine the necessary corrections and repeat as necessary steps 1 through 9 above.
11. Record deviations and the details of corrector positions on the deviation card to be posted near the compass.

12. Swing for residual degaussed deviations with the degaussing circuits properly energized.
13. Record deviations for degaussed conditions on the deviation card.

The above check-off list describes a simplified method of adjusting compasses, designed to serve as a workable outline for the novice who chooses to follow a step-by-step procedure. The dockside tests and adjustments are essential as a foundation for the adjustments at sea. Neglecting the dockside procedures may lead to spurious results or needless repetition of the procedures at sea. Give careful consideration to these dockside checks prior to making the final adjustment. This will allow time to repair or replace faulty compasses, anneal or replace magnetized spheres or Flinders bars, realign the binnacle, move a gyro repeater if it is affecting the compass, or to make any other necessary preliminary repairs.

Expeditious compass adjustment depends upon the application of the various correctors in a logical sequence so as to achieve the final adjustment with a minimum number of steps. The above check-off list accomplishes this purpose. Figure 607 presents the various compass errors and their correction in condensed form. Frequent, careful observations should be made to determine the constancy of deviations, and results should be systematically recorded. Significant changes in deviation will indicate the need for readjustment.

To avoid Gaussin error (section 636) when adjusting and swinging ship for residuals, the ship should be steady on the desired heading for at least 2 minutes prior to observing the deviation.

602. The Magnetic Compass And Magnetism

The principle of the present day magnetic compass is no different from that of the compasses used by ancient mariners. It consists of a magnetized needle, or an array of needles, allowed to rotate in the horizontal plane. The superiority of the present day compasses over ancient ones results from a better knowledge of the laws of magnetism which govern the behavior of the compass and from greater precision in construction.

Any piece of metal on becoming magnetized will develop regions of concentrated magnetism called **poles**. Any such magnet will have at least two poles of opposite polarity. Magnetic force (flux) lines connect one pole of such a magnet with the other pole. The number of such lines per unit area represents the intensity of the magnetic field in that area. If two such magnetic bars or magnets are placed close to each other, the like poles will repel each other and the unlike poles will attract each other.

Magnetism can be either **permanent** or **induced**. A bar having permanent magnetism will retain its magnetism when it is removed from the magnetizing field. A bar having induced magnetism will lose its magnetism when removed from the magnetizing field. Whether or not a bar will retain its magnetism on removal from the magnetizing field will depend on the strength of that field, the degree of hardness of the iron (retentivity), and also upon the amount of physical stress applied to the bar while in the magnetizing field. The harder the iron, the more permanent will be the magnetism acquired.

603. Terrestrial Magnetism

Consider the earth as a huge magnet surrounded by magnetic flux lines connecting its two **magnetic poles**. These magnetic poles are near, but not coincidental with, the earth's geographic poles. Since the north seeking end of a compass needle is conventionally called the **north pole**, or **positive pole**, it must therefore be attracted to a **south pole**, or **negative pole**.

Figure 603a illustrates the earth and its surrounding magnetic field. The flux lines enter the surface of the earth at different angles to the horizontal, at different magnetic atitudes. This angle is called the **angle of magnetic dip**,

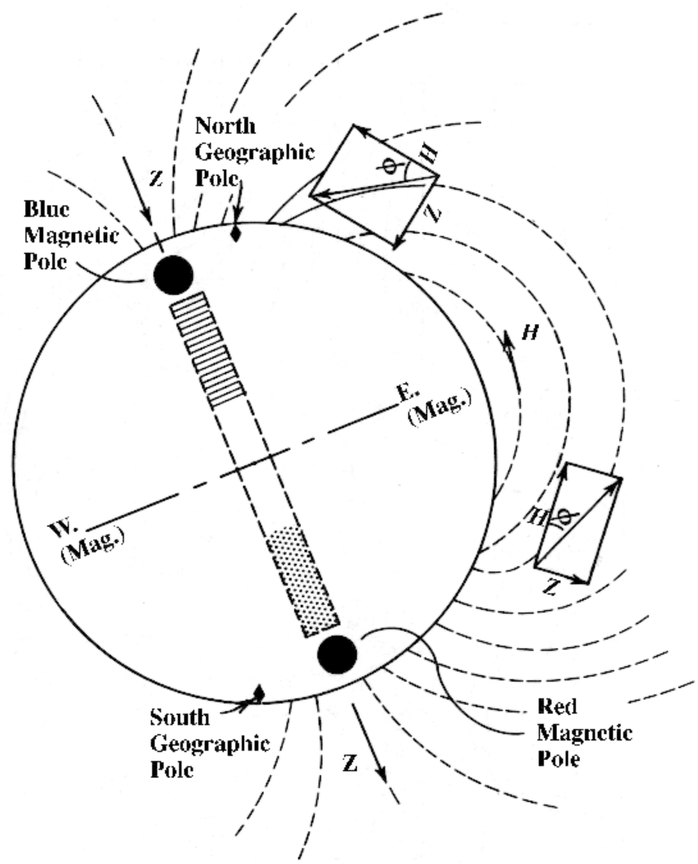


Figure 603aTerrestrial magnetism.

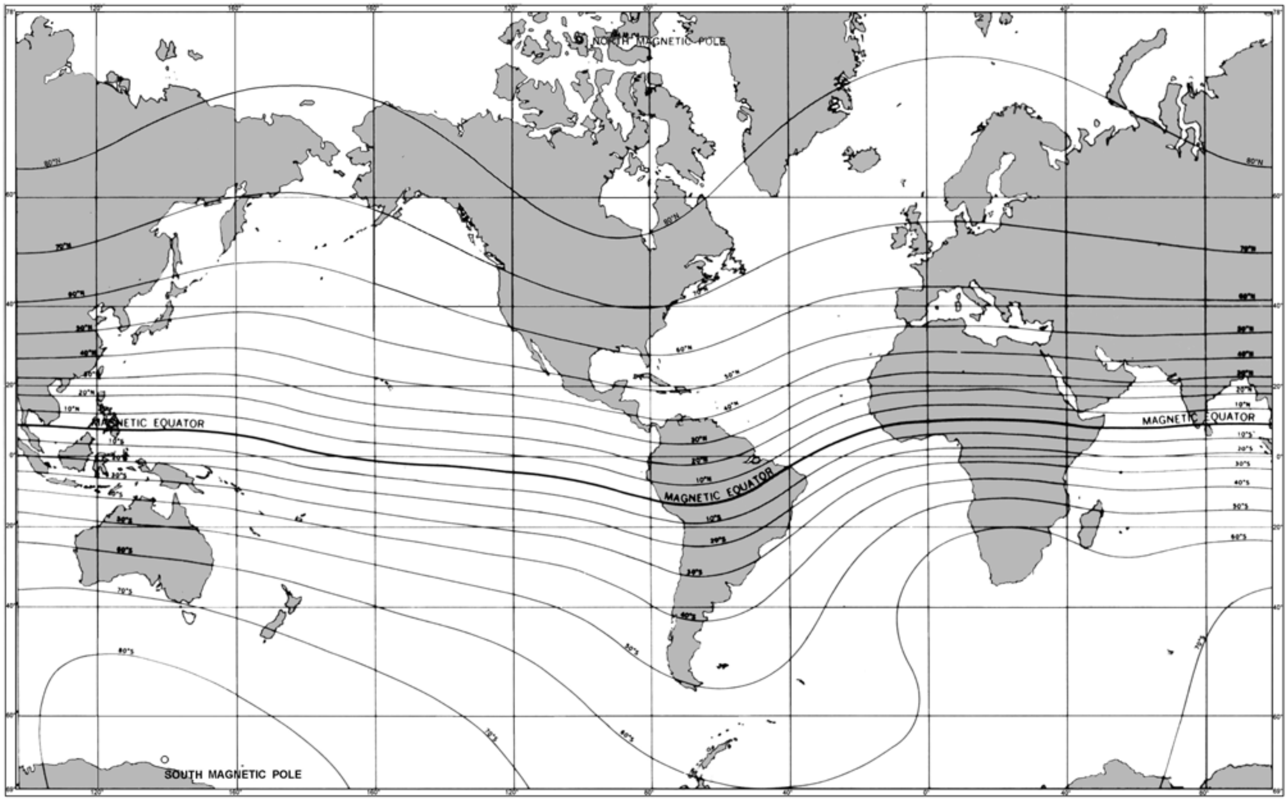


Figure 603b. Magnetic dip chart, a simplification of chart 30.

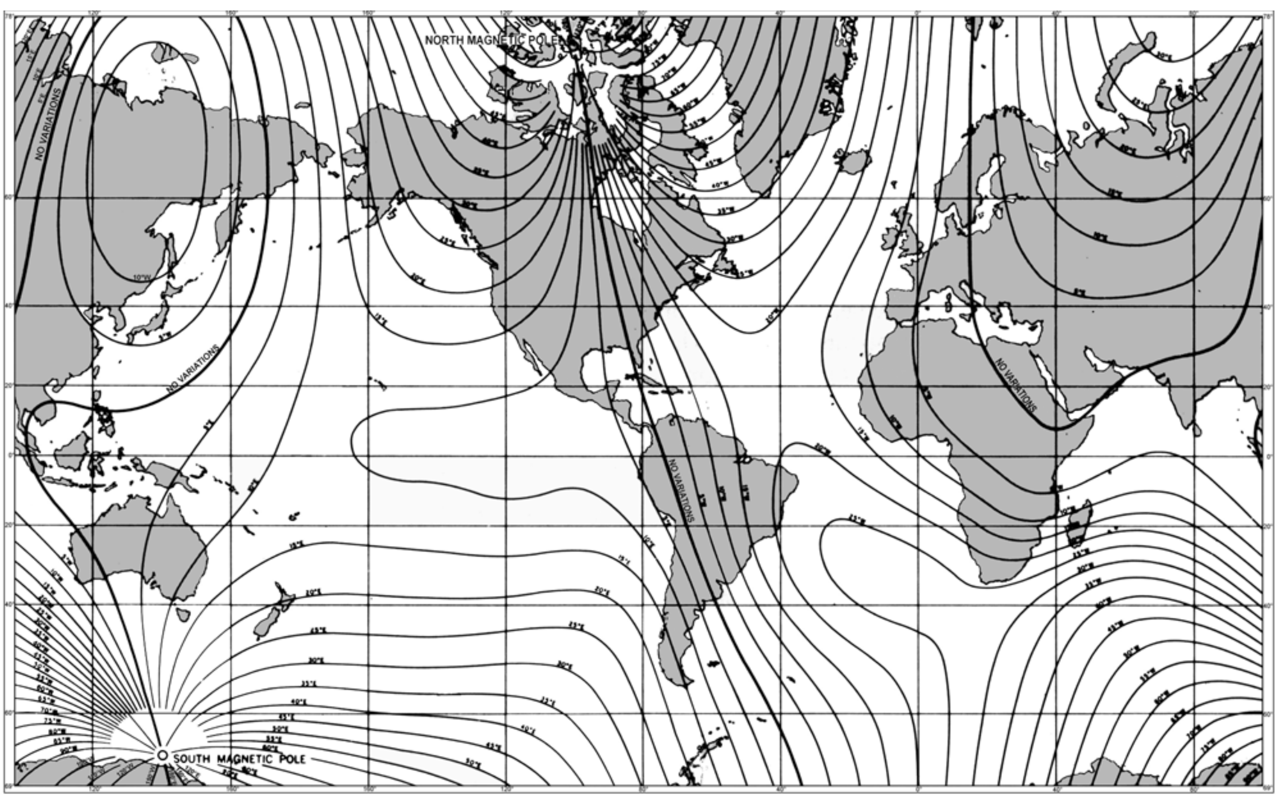


Figure 603c. Magnetic variation chart, a simplification of chart 42.

θ, and increases from 0°, at the magnetic equator, to 90° at the magnetic poles. The total magnetic field is generally considered as having two components: H, the horizontal component; and Z, the vertical component. These components change as the angle θ, changes, such that H is maximum at the magnetic equator and decreases in the direction of either pole; Z is zero at the magnetic equator and increases in the direction of either pole. The values of magnetic dip may be found on **Chart 30** (shown simplified in Figure 603b). The values of H and Z may be found on charts 33 and 36.

Since the magnetic poles of the earth do not coincide with the geographic poles, a compass needle in line with the earth's magnetic field will not indicate true north, but magnetic north. The angular difference between the true meridian (great circle connecting the geographic poles) and the magnetic meridian (direction of the lines of magnetic flux) is called **variation**. This variation has different values at different locations on the earth. These values of magnetic variation may be found on Chart 42 (shown simplified in Figure 603c), on pilot charts, and on the compass rose of navigational charts. The variation for most given areas undergoes an annual change, the amount of which is also noted on charts.

604. Ship's Magnetism

A ship under construction or major repair will acquire permanent magnetism due to hammering and jarring while sitting stationary in the earth's magnetic field. After launching, the ship will lose some of this original magnetism as a result of vibration and pounding in varying magnetic fields, and will eventually reach a more or less stable magnetic condition. The magnetism which remains is the **permanent magnetism** of the ship.

The fact that a ship has permanent magnetism does not mean that it cannot also acquire induced magnetism when placed in the earth's magnetic field. The magnetism induced in any given piece of soft iron is a function of the field intensity, the alignment of the soft iron in that field, and the physical properties and dimensions of the iron. This induced magnetism may add to, or subtract from, the permanent magnetism already present in the ship, depending on how the ship is aligned in the magnetic field. The softer the iron, the more readily it will be magnetized by the earth's magnetic field, and the more readily it will give up its magnetism when removed from that field.

The magnetism in the various structures of a ship, which tends to change as a result of cruising, vibration, or aging, but which does not alter immediately so as to be properly termed induced magnetism, is called **subpermanent magnetism**. This magnetism, at any instant, is part of the ship's permanent magnetism, and consequently must be corrected by permanent magnet correctors. It is the principal cause of deviation changes on a magnetic compass. Subsequent reference to permanent magnetism will refer to the apparent permanent magnetism which includes the existing permanent and subpermanent magnetism.

A ship, then, has a combination of permanent, subpermanent, and induced magnetism. Therefore, the ship's apparent permanent magnetic condition is subject to change from deperming, excessive shocks, welding, and vibration. The ship's induced magnetism will vary with the earth's magnetic field strength and with the alignment of the ship in that field.

605. Magnetic Adjustment

A rod of soft iron, in a plane parallel to the earth's horizontal magnetic field, H, will have a north pole induced in the end toward the north geographic pole and a south pole induced in the end toward the south geographic pole. This same rod in a horizontal plane, but at right angles to the horizontal earth's field, would have no magnetism induced in it, because its alignment in the magnetic field is such that there will be no tendency toward linear magnetization, and the rod is of negligible cross section. Should the rod be aligned in some horizontal direction between those headings which create maximum and zero induction, it would be induced by an amount which is a function of the angle of alignment. If a similar rod is placed in a vertical position in northern latitudes so as to be aligned with the vertical earth's field Z, it will have a south pole induced at the upper end and a north pole induced at the lower end. These polarities of vertical induced magnetization will be reversed in southern latitudes.

The amount of horizontal or vertical induction in such rods, or in ships whose construction is equivalent to combinations of such rods, will vary with the intensity of H and Z, heading and heel of the ship.

The magnetic compass must be corrected for the vessel's permanent and induced magnetism so that its operation approximates that of a completely nonmagnetic vessel. Ship's magnetic conditions create magnetic compass deviations and sectors of sluggishness and unsteadiness. **Deviation** is defined as deflection right or left of the magnetic meridian. Adjusting the compass consists of arranging magnetic and soft iron **correctors** about the binnacle so that their effects are equal and opposite to the effects of the magnetic material in the ship.

The total permanent magnetic field effect at the compass may be broken into three components, mutually 90° apart, as shown in Figure 605a.

The vertical permanent component tilts the compass card, and, when the ship rolls or pitches, causes oscillating deflections of the card. Oscillation effects which accompany roll are maximum on north and south compass headings, and those which accompany pitch are maximum on east and west compass headings.

The horizontal B and C components of permanent magnetism cause varying deviations of the compass as the ship swings in heading on an even keel. Plotting these deviations against compass heading yields the sine and cosine curves shown in Figure 605b. These deviation curves are called semicircular curves because they reverse direction by 180°.

A vector analysis is helpful in determining deviations or

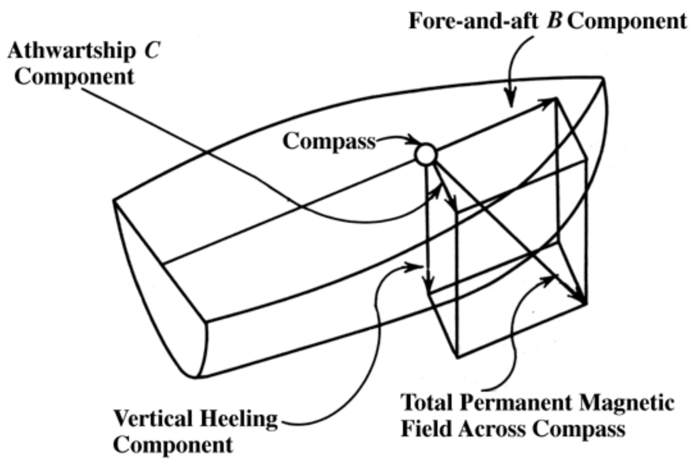


Figure 605a. Components of permanent magnetic field.

the strength of deviating fields. For example, a ship as shown in Figure 605c on an east magnetic heading will subject its compass to a combination of magnetic effects; namely, the earth's horizontal field H, and the deviating field B, at right angles to the field H. The compass needle will align itself in the resultant field which is represented by the vector sum of H and B, as shown. A similar analysis will reveal that the resulting directive force on the compass would be maximum on a north heading and minimum on a south heading because the deviations for both conditions are zero.

The magnitude of the deviation caused by the permanent B magnetic field will vary with different values of H; hence, deviations resulting from permanent magnetic fields will vary with the magnetic latitude of the ship.

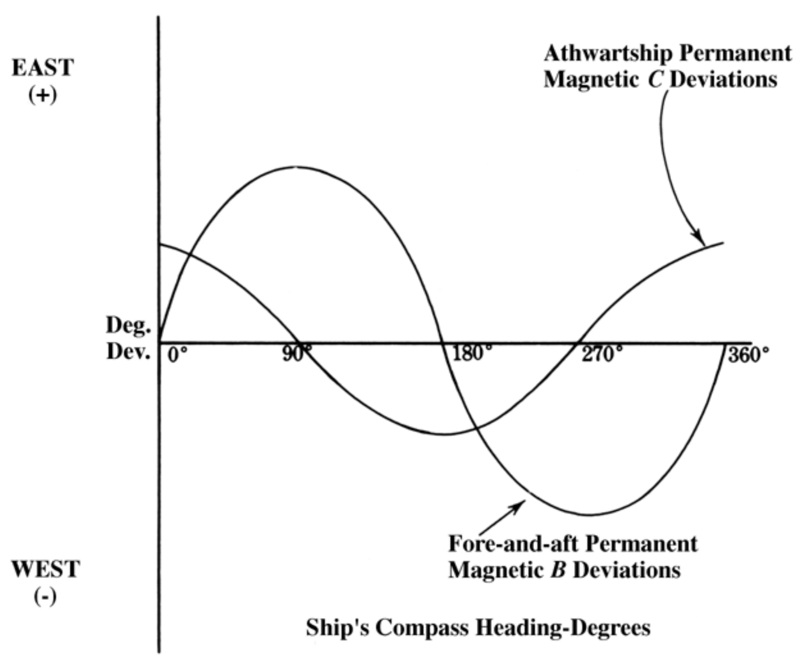


Figure 605b. Permanent magnetic deviation effects.

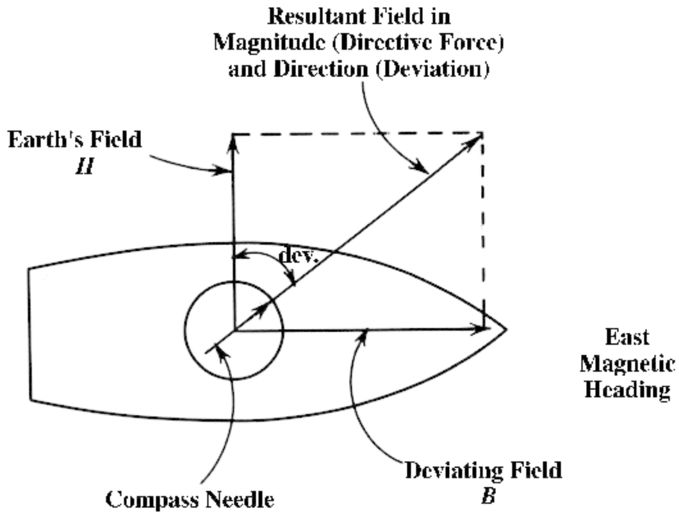


Figure 605c. General force diagram.

606. Induced Magnetism And Its Effects On The Compass

Induced magnetism varies with the strength of the surrounding field, the mass of metal, and the alignment of the metal in the field. Since the intensity of the earth's magnetic field varies over the earth's surface, the induced magnetism in a ship will vary with latitude, heading, and heel of the ship.

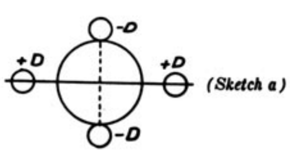
With the ship on an even keel, the resultant vertical induced magnetism, if not directed through the compass itself, will create deviations which plot as a semicircular deviation curve. This is true because the vertical induction changes magnitude and polarity only with magnetic latitude and heel, and not with heading of the ship. Therefore, as long as the ship is in the same magnetic latitude, its vertical induced pole swinging about the compass will produce the same effect on the compass as a permanent pole swinging about the compass.

The earth's field induction in certain other unsymmetrical arrangements of horizontal soft iron create a constant A deviation curve. In addition to this magnetic A error, there are constant A deviations resulting from: (1) physical misalignments of the compass, pelorus, or gyro; (2) errors in calculating the sun's azimuth, observing time, or taking bearings.

The nature, magnitude, and polarity of all these induced effects are dependent upon the disposition of metal, the symmetry or asymmetry of the ship, the location of the binnacle, the strength of the earth's magnetic field, and the angle of dip.

Coefficient	Type deviation curve	Compass headings of maximum deviation	Causes of such errors	Correctors for such errors	Magnetic or compass headings on which to apply correctors
A	Constant.	Same on all.	Human-error in calculations _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ Physical-compass, gyro, pelorus alignment _ _ _ _ _ _ _ _ _ Magnetic-unsymmetrical arrangements of horiz. soft iron.	Check methods and calculations Check alignments Rare arrangement of soft iron rods.	Any.
B	Semicircular $\sin\phi$.	090˚ 270˚	Fore-and-aft component of permanent magnetic field _ _ _ _ _ Induced magnetism in unsymmetrical vertical iron forward or aft of compass.	Fore-and-aft *B* magnets Flinders bar (forward or aft)	090˚ or 270˚.
C	Semicircular $\cos\phi$.	000˚ 180˚	Athwartship component of permanent magnetic field- - - - - - - Induced magnetism in unsymmetrical vertical iron port or starboard of compass.	Athwartship *C* magnets Flinders bar (port or starboard)	000˚ or 180˚.
D	Quadrantral $\sin 2\phi$.	045˚ 135˚ 225˚ 315˚	Induced magnetism in all symmetrical arrangements of horizontal soft iron.	Spheres on appropriate axis. (athwartship for +D) (fore and aft for -D) *See sketch a*	045˚, 135˚, 225˚, or 315˚.
E	Quadrantral $\cos 2\phi$.	000˚ 090˚ 180˚ 270˚	Induced magnetism in all unsymmetrical arrangements of horizontal soft iron.	Spheres on appropriate axis. (port fwd.-stb'd for +E) (stb'd fwd.-port aft for -E) *See sketch b*	000˚, 090˚, 180˚, or 270˚.
Heeling	Oscillations with roll or pitch. Deviations with constant list.	000˚ } roll 180˚ 090˚ } pitch 270˚	Change in the horizontal component of the induced or permanent magnetic fields at the compass due to rolling or pitching of the ship.	Heeling magnet (must be readjusted for latitude changes).	090˚ or 270˚ with dip needle. 000˚ or 180˚ while rolling.

Deviation $= A + B\sin\phi + C\cos\phi + D\sin 2\phi + E\cos 2\phi$ (ϕ = compass heading)



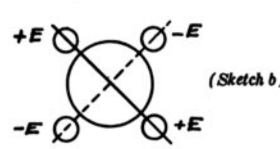


Figure 607. Summary of compass errors and adjustments.

Certain heeling errors, in addition to those resulting from permanent magnetism, are created by the presence of both horizontal and vertical soft iron which experience changing induction as the ship rolls in the earth's magnetic field. This part of the heeling error will naturally change in magnitude with changes of magnetic latitude of the ship. Oscillation effects accompanying roll are maximum on north and south headings, just as with the permanent magnetic heeling errors.

607. Adjustments And Correctors

Since some magnetic effects are functions of the vessel's magnetic latitude and others are not, each individual effect should be corrected independently. Furthermore, to make the corrections, use (1) permanent magnet correctors to compensate for permanent magnetic fields at the compass, and (2) soft iron correctors to compensate for induced magnetism. The compass binnacle provides support for both the compass and such correctors. Typical binnacles hold the following correctors:

1. Vertical permanent **heeling magnet** in the central vertical tube.
2. Fore-and-aft **B permanent magnets** in their trays.
3. Athwartship **C permanent magnets** in their trays.
4. Vertical soft iron **Flinders bar** in its external tube.
5. Soft iron **quadrantal spheres**.

The heeling magnet is the only corrector which corrects for both permanent and induced effects. Therefore, it must be adjusted occasionally for changes in ship's latitude. However, any movement of the heeling magnet will require readjustment of other correctors.

Figure 607 summarizes all the various magnetic conditions in a ship, the types of deviation curves they create, the correctors for each effect, and headings on which each corrector is adjusted. Apply the correctors symmetrically and as far away from the compass as possible. This preserves the uniformity of magnetic fields about the compass needle array.

Fortunately, each magnetic effect has a slightly different characteristic curve. This makes identification and correction convenient. Analyzing a complete deviation curve for its different components allows one to anticipate the necessary corrections.

COMPASS OPERATION

608. Effects Of Errors On The Compass

An uncorrected compass suffers large deviations and sluggish, unsteady operation. These conditions may be associated with the maximum and minimum directive force acting on the compass. The maximum deviation occurs at the point of average directive force; and the zero deviations occur at the points of maximum and minimum directive force.

Applying correctors to reduce compass deviation effects compass error correction. Applying correctors to equalize the directive forces across the compass position could also effect compass correction. The deviation method is most often used because it utilizes the compass itself as the correction indicator. Equalizing the directive forces would require an additional piece of test and calibration equipment.

Occasionally, the permanent magnetic effects at the location of the compass are so large that they overcome the earth's directive force, H. This condition will not only create sluggish and unsteady sectors, but may even freeze the compass to one reading or to one quadrant, regardless of the heading of the ship. Should the compass become so frozen, the polarity of the magnetism which must be attracting the compass needles is indicated; hence, correction may be effected simply by the application of permanent magnet correctors, in suitable quantity to neutralize this magnetism. Whenever such adjustments are made, it would be well to have the ship placed on a heading such that the unfreezing of the compass needles will be immediately evident. For example, a ship whose compass is frozen to a north reading would require fore-and-aft B corrector magnets with the positive ends forward in order to neutralize the existing negative pole which attracted the compass. If made on an east heading, such an adjustment would be practically complete when the compass card was freed to indicate an east heading.

609. Reasons For Correcting Compass

There are several reasons for correcting the errors of the magnetic compass:

1. It is easier to use a magnetic compass if the deviations are small.

2. Even known and compensated for deviation introduces error because the compass operates sluggishly and unsteadily when deviation is present.

3. Even though the deviations are compensated for, they will be subject to appreciable change as a function of heel and magnetic latitude.

Once properly adjusted, the magnetic compass deviations should remain constant until there is some change in the magnetic condition of the vessel resulting from magnetic treatment, shock from gunfire, vibration, repair, or structural changes. Frequently, the movement of nearby guns, doors, gyro repeaters, or cargo affects the compass greatly.

DETAILED PROCEDURES FOR COMPASS ADJUSTMENT

610. Dockside Tests And Adjustments

Section 601, the Adjustment Checkoff List, gives the physical checks required before beginning an adjustment. The adjustment procedure assumes that these checks have been completed. The navigator will avoid much delay by making these checks before starting the magnet and soft iron corrector adjustments. The most important of these checks are discussed below.

Should the compass have a small bubble, add compass fluid through the filling plug on the compass bowl. If an appreciable amount of compass liquid has leaked out, check the sealing gasket and filling plug for leaks.

Take the compass to a place free from all magnetic influences except the earth's magnetic field for tests of **moment** and **sensibility**. These tests involve measurements of the time of vibration and the ability of the compass card to return to a consistent reading after deflection. These tests will indicate the condition of the pivot, jewel, and magnetic strength of the compass needles.

Next, check the spheres and Flinders bar for residual magnetism. Move the spheres as close to the compass as possible and slowly rotate each sphere separately. Any appreciable deflection (2° or more) of the compass needles resulting from this rotation indicates residual magnetism in the spheres. The Flinders bar magnetization check is preferably made with the ship on an east or west compass heading. To make this check: (a) note the compass reading with the Flinders bar in the holder; (b) invert the Flinders bar in the holder and again note the compass reading. Any appreciable difference (2° or more) between these observed readings indicates residual magnetism in the Flinders bar. Spheres or Flinders bars which show signs of such residual magnetism should be **annealed**, i.e., heated to a dull red and allowed to cool slowly.

Correct alignment of the lubber's line of the compass, gyro repeater, and pelorus with the fore-and-aft line of the ship is important. Any misalignment will produce a constant error in the deviation curve. All of these instruments may be aligned correctly with the fore-and-aft line of the ship by using the azimuth circle and a metal tape measure. Should the instrument be located on the centerline of the ship, a sight is taken on a mast or other object on the centerline. If the instrument is not on the centerline, measure the distance from the centerline of the ship to the center of the instrument. Mark this distance off from the centerline forward or abaft the compass and place reference marks on the deck. Take sights on these marks.

Align the compass so that the compass' lubber's line is parallel to the fore-and-aft line of the ship. Steering compasses may occasionally be deliberately misaligned in order to correct for any magnetic A error present, as discussed in section 611.

Adjust the Flinders bar first because it is subject to induction from several of the correctors and its adjustment is not dependent on any single observation. To adjust the Flinders bar, use one of the following methods:

1. Use deviation data obtained at two different magnetic latitudes to calculate the proper length of Flinders bar for any particular compass location. Sections 622 through 624 contain details on acquiring the data and making the required calculations.

2. If the above method is impractical, set the Flinders bar length by:

   a. Using a Flinders bar length determined by other ships of similar structure.

   b. Studying the arrangement of masts, stacks, and other vertical structures and estimating the Flinders bar length required.

If these methods are not suitable, omit the Flinders bar until the required data are acquired.

The iron sections of Flinders bar should be continuous and placed at the top of the tube with the longest section at the top. Wooden spacers are used at the bottom of the tube.

Having adjusted the length of Flinders bar, place the spheres on the bracket arms at an approximate position. If the compass has been adjusted previously, place the spheres at the position indicated by the previous deviation table. In the event the compass has never been adjusted, place the spheres at the midpoint on the bracket arms.

The next adjustment is the positioning of the heeling magnet using a properly balanced dip needle. Section 637 discusses this procedure.

These three dockside adjustments (Flinders bar, quadrantal spheres, and heeling magnet) will properly establish the conditions of mutual induction and shielding of the compass. This minimizes the steps required at sea to complete the adjustment.

611. Expected Errors

Figure 607 lists six different coefficients or types of deviation errors with their causes and corresponding correctors. A discussion of these coefficients follows:

The **A error** is caused by the miscalculation of azimuths or by physical misalignments rather than magnetic effects of unsymmetrical arrangements of horizontal soft iron. Thus,

checking the physical alignments at dockside and making careful calculations will minimize the A error. Where an azimuth or bearing circle is used on a standard compass to determine deviations, any observed A error will be solely magnetic A error because such readings are taken on the face of the compass card rather than at the lubber's line of the compass. On a steering compass where deviations are obtained by a comparison of the compass lubber's line reading with the ship's magnetic heading, as determined by pelorus or gyro, any observed A error may be a combination of magnetic A and mechanical A (misalignment). These facts explain the procedure in which only mechanical A is corrected on the standard compass, by realignment of the binnacle, and both mechanical A and magnetic A errors are corrected on the steering compass by realignment of the binnacle. On the standard compass, the mechanical A error may be isolated from the magnetic A error by making the following observations simultaneously:

1. Record a curve of deviations by using an azimuth (or bearing) circle. Any A error found will be solely magnetic A.

2. Record a curve of deviations by comparison of the compass lubber's line reading with the ship's magnetic heading as determined by pelorus or by gyro. Any A error found will be a combination of mechanical A and magnetic A.

3. The mechanical A on the standard compass is then found by subtracting the A found in the first instance from the total A found in the second instance, and is corrected by rotating the binnacle in the proper direction by that amount. It is neither convenient nor necessary to isolate the two types of A on the steering compass and all A found by using the pelorus or gyro may be removed by rotating the binnacle in the proper direction.

The **B error** results from both the fore-and-aft permanent magnetic field across the compass and a resultant unsymmetrical vertical induced effect forward or aft of the compass. The former is corrected by the use of fore-and-aft B magnets, and the latter is corrected by the use of the Flinders bar forward or aft of the compass. Because the Flinders bar setting is a dockside adjustment, any remaining B error is corrected by the use of fore-and-aft B magnets.

The **C error** results from the athwartship permanent magnetic field across the compass and a resultant unsymmetrical vertical induced effect athwartship of the compass. The former is corrected by the use of athwartship C magnets, and the latter by the use of the Flinders bar to port or starboard of the compass. Because the vertical induced effect is very rare, the C error is corrected by athwartship C magnets only.

The **D error** is due only to induction in the symmetrical arrangements of horizontal soft iron, and requires correction by spheres, generally athwartship of the compass.

E error of appreciable magnitude is rare, since it is caused by induction in the unsymmetrical arrangements of horizontal soft iron. When this error is appreciable it may be corrected by slewing the spheres, as described in section 620.

As stated previously, the heeling error is adjusted at dockside with a **balanced dip needle** (see section 637).

As the above discussion points out, certain errors are rare and others are corrected at dockside. Therefore, for most ships, only the B, C, and D errors require at sea correction. These errors are corrected by the fore-and-aft B magnets, athwartship C magnets, and quadrantal spheres respectively.

612. Study Of Adjustment Procedure

Inspecting the B, C, and D errors pictured in Figure 612a demonstrates a definite isolation of deviation effects on *cardinal* compass headings.

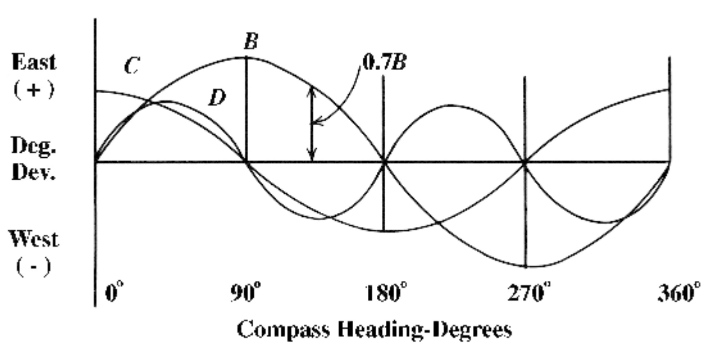


Figure 612a. B, C, and D deviation effects.

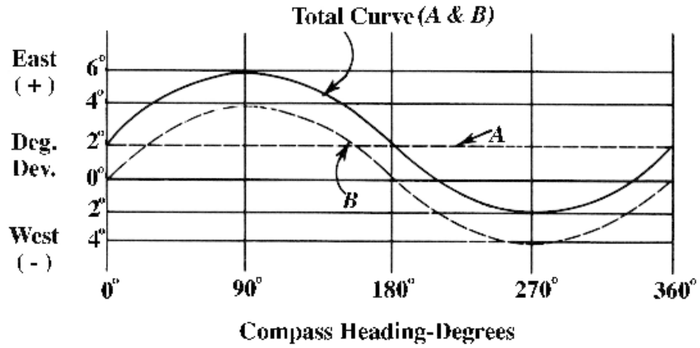


Figure 612b. A and B deviation.

For example, on 090° or 270° compass headings, the only deviation which is effective is that due to B. This isolation, and the fact that the B effect is greatest on these two headings, make these headings convenient for B correction. Correction of the B deviation on a 090° heading will correct the B deviation on the 270° heading by the same amount but in the opposite direction and naturally, it will not change the deviations on the 000° and 180° headings, except where B errors are large. However, the total deviation on all the intercardinal headings will be shifted in the same direction as the adjacent 090° or 270° deviation correction, but only by seven-tenths (0.7) of that amount, since the sine of 45° equals 0.707. The same convenient isolation of effects and corrections of C error will also change the deviations on all the intercardinal headings by the seven-tenths rule.

Note that only after correcting the B and C errors on the cardinal headings, and consequently their proportional values of the total curve on the intercardinal headings, can the D error be observed separately on any of the intercardinal headings. The D error may then be corrected by use of the spheres on any intercardinal heading. Correcting D error will, as a rule, change the deviations on the intercardinal headings only, and not on the cardinal headings. Only when the D error is excessive, the spheres are magnetized, or the permanent magnet correctors are so close as to create excessive induction in the spheres will there be a change in the deviations on cardinal headings as a result of sphere adjustments. Although sphere correction does not generally correct deviations on cardinal headings, it does improve compass stability on these headings.

If it were not for the occasional A or E errors, adjusting observed deviations to zero on two adjacent cardinal headings and then on the intermediate intercardinal heading would be sufficient. However, Figure 612b, showing a combination of A and B errors, illustrates why the adjusting procedure must include correcting deviations on more than the three essential headings.

Assuming no A error existed in the curve illustrated in Figure 612b, and the total deviation of 6° E on the 090° heading were corrected with B magnets, the error on the 270° heading would be 4° E due to B overcorrection. If this 4° E error were taken out on the 270° heading, the error on the 090° heading would then be 4° E due to B undercorrection. To eliminate this endlessly iterative process and correct the B error to the best possible flat curve, split this 4° E difference, leaving 2° E deviation on each opposite heading. This would, in effect correct the B error, leaving only the A error of 2° E which must be corrected by other means. It is for this reason that, (1) splitting is done between the errors noted on opposite headings, and (2) good adjustments entail checking on all headings rather than on the fundamental three.

613. Adjustment Procedures At Sea

Before proceeding with the adjustment at sea the following precautions should be observed:

1. Secure all effective magnetic gear in the normal seagoing position.

2. Make sure the degaussing coils are secured, using the reversal sequence, if necessary (See section 643).

The adjustments are made with the ship on an even keel, swinging from heading to heading slowly, and after steadying on each heading for at least 2 minutes to avoid Gaussin error.

Most adjustments can be made by trial and error, or by routine procedure such as the one presented in section 601. However, the procedures presented below provide analytical methods in which the adjuster is always aware of the errors' magnitude on all headings as a result of his movement of the different correctors.

Analysis Method. A complete deviation curve can be taken for any given condition, and an estimate made of all the approximate coefficients. See section 615. From this estimate, the approximate coefficients are established and the appropriate corrections are made with reasonable accuracy on a minimum number of headings. If the original deviation curve has deviations greater than 20°, rough adjustments should be made on two adjacent cardinal headings before recording curve data for such analysis. The mechanics of

Heading by compass	1 Original deviation curve	2 Anticipated curve after first correcting *A* = 1.0° E	3 Anticipated curve after next correcting *B* = 12.0° E	4 Anticipated curve after next correcting *C* = 8.0° E	5 Anticipated curve after next correcting *D* = 5.0° E	6 Anticipated curve after next correcting *E* = 1.5° E
Degrees	*Degrees*	*Degrees*	*Degrees*	*Degrees*	*Degrees*	*Degrees*
000	10.5 E.	9.5 E.	9.5 E.	1.5 E.	1.5 E.	0.0
045	20.0 E.	19.0 E.	10.6 E.	5.0 E.	0.0	0.0
090	11.5 E.	10.5 E.	1.5 W.	1.5 W.	1.5 W.	0.0
135	1.2 W.	2.2 W.	10.6 W.	5.0 W.	0.0	0.0
180	5.5 W.	6.5 W.	6.5 W.	1.5 E.	1.5 E.	0.0
225	8.0 W.	9.0 W.	0.6 W.	5.0 E.	0.0	0.0
270	12.5 W.	13.5 W.	1.5 W.	1.5 W.	1.5 W.	0.0
315	6.8 W.	7.8 W.	0.6 E.	5.0 W.	0.0	0.0

Figure 613a. Tabulating anticipated deviations.

applying correctors are presented in Figure 601. A method of tabulating the anticipated deviations after each correction is illustrated in Figure 613a. The deviation curve used for illustration is the one which is analyzed in section 615. Analysis revealed these coefficients:

A = 1.0˚ E
B = 12.0˚ E
C = 8.0˚ E
D = 5.0˚ E
E = 1.5˚ E

One-Swing Method. More often it is desirable to begin adjustment immediately, eliminating the original swing for deviations and the estimate of approximate coefficients. In this case the above problem would be solved by tabulating data and anticipating deviation changes as the corrections are made. Figure 613b illustrates this procedure. Note that a new column of values is started after each change is made. This method of tabulation enables the adjuster to calculate the new residual deviations each time a corrector is changed, so that a record of deviations is available at all times during the swing. Arrows indicate where each change is made.

Since the B error is generally greatest, it is corrected first. Therefore, on a 090° heading the 11.5° E deviation is corrected to approximately zero by using fore-and-aft B magnets. A lot of time need not be spent trying to reduce this deviation to exactly zero since the B coefficient may not be exactly 11.5° E, and some splitting might be desirable later. After correcting on the 090° heading, the swing would then be continued to 135° where a 9.2° W error would be observed. This deviation is recorded, but no correction is made because the quadrant error is best corrected after the deviations on all four cardinal headings have been corrected. The deviation on the 180° heading would be observed as 5.5° W. Since this deviation is not too large and splitting may be necessary later, it need not be corrected at this time. Continuing the swing to 225° a 0.0° deviation would be observed and recorded. On the 270° heading the observed error would be 1.0° W, which is compared with 0.0° deviation on the opposite 090° heading. This could be split, leaving 0.5° W deviation on both 090° and 270°, but since this is so small it may be left uncorrected. On 315˚ the observed deviation would be 1.2° E. At 000° a deviation of 10.5° E would be observed and compared with 5.5° W on 180°. Analysis of the deviations on 000° and 180° headings reveals an 8.0° E, C error, which should then be corrected with athwartship C magnets leaving 2.5° E deviation on both the 000° and 180° headings.

Heading	First obser-vation	Observed deviations after correcting *B* = 11.5° E	Anticipated deviations after correcting *C* = 8.0° E	Anticipated deviations after correcting *D* =5.0° E	Anticipated deviations after correcting *A* = 1.0° E	Anticipated deviations after correcting *E* = 1.5° E
Degrees	*Degrees*	*Degrees*	*Degrees*	*Degrees*	*Degrees*	*Degrees*
000	...	10.5 E.→	2.5 E.	2.5 E.	1.5 E.	0.0
045	...	...	6.4 E.→	1.4 E.→	0.4 E.	0.4 E.
090	11.5 E.→	0.0	0.0	0.0	1.0 W.→	0.5 E.
135	...	9.2 W.	3.6 W.	1.4 E.	0.4 E.	0.4 E.
180	...	5.5 W.	2.5 E.	2.5 E.	1.5 E.	0.0
225	...	0.0	5.6 E.	0.6 E.	0.4 W.	0.4 W.
270	...	1.0 W.	1.0 W.	1.0 W.	2.0 W.	0.5 W.
315	...	1.2 E.	4.4 W.	0.6 E.	0.4 W.	0.4 W.

Figure 613b. Tabulating anticipated deviations by the one-swing.

All the deviations in column two are now recalculated on the basis of such an adjustment at 000° heading and entered in column three. Continuing the swing, the deviation on 045° would then be noted as 6.4° E. Knowing the deviations on all intercardinal headings, it is now possible to estimate the approximate coefficient D. D is 5.0° E so the 6.4° E deviation on 045° is corrected to 1.4° E and new anticipated values are recorded in another column. This anticipates a fairly good curve, an estimate of which reveals, in addition to the B of 0.5° E which was not considered large enough to warrant correction, an A of 1.0° E and an E of 1.5° E. These A and E errors may or may not be corrected, as practical. If they are corrected, the subsequent steps would be as indicated in the last two columns. Now the ship has made only one swing, all corrections have been made, and some idea of the expected curve is available.

614. Deviation Curves

The last step, after completion of either of the above methods of adjustment, is to secure all correctors in position and to swing for residual deviations. These residual deviations are for undegaussed conditions of the ship, which should be recorded together with details of corrector positions. Figure 614 illustrates both sides of NAVSEA 3120/4 with proper instructions and sample deviation and Flinders bar data. Should the ship be equipped with degaussing coils, a swing for residual deviations under degaussed conditions should also be made and data recorded on NAVSEA 3120/4.

On these swings, exercise extreme care in taking bearings or azimuths and in steadying down on each heading since this swing is the basis of standard data for the particular compass. If there are any peculiar changeable errors, such as movable guns, listing of the ship, or anticipated decay from deperming, which would effect the reliability of the compass, they should also be noted on the deviation card at this time. Section 639 discusses these many sources of error in detail.

If the Flinders bar adjustment is not based on accurate

MAGNETIC COMPASS TABLE NAVSEA RPT. 3530-2
NAVSEA 3120/4 (REV. 6-72) (FRONT) *(Formerly NAVSHIPS 3104)*
S/N 0105-601-9521

U.S.S. ______ NO. ______ (BB, CL, DD, etc.)
[X] PILOT HOUSE [ ] SECONDARY CONNING STATION [ ] OTHER ______
BINNACLE TYPE [X] NAVY ST'D [ ] OTHER ______
COMPASS 7-1/2" MAKE C.G. Conn SERIAL NO. 8560
TYPE CC COILS "K" DATE 9 September 1975

READ INSTRUCTIONS ON BACK BEFORE STARTING ADJUSTMENT

SHIPS HEAD MAGNETIC	DEVIATIONS DG OFF	DEVIATIONS DG ON	SHIPS HEAD MAGNETIC	DEVIATIONS DG OFF	DEVIATIONS DG ON
0	0.5E	0.5E	180	0.5W	0.0
15	1.0E	1.0E	195	1.0W	0.5W
30	1.5E	1.5E	210	1.0W	1.0W
45	2.0E	1.5E	225	1.5W	1.5W
60	2.0E	2.0E	240	2.0W	2.0W
75	2.5E	2.5E	255	2.0W	2.5W
90	2.5E	3.0E	270	1.5W	2.0W
105	2.0E	2.5E	285	1.0W	1.5W
120	1.5E	2.0E	300	1.0W	1.0W
135	1.5E	1.5E	315	0.5W	0.5W
150	1.0E	1.0E	330	0.5W	0.5W
165	0.0	0.5E	345	0.0	0.0

DEVIATIONS DETERMINED BY: [ ] SUN'S AZIMUTH [X] GYRO [ ] SHORE BEARINGS

B 6 MAGNETS RED [ ] FORE [X] AFT AT 12" FROM COMPASS CARD
C 4 MAGNETS RED [ ] PORT [X] STBD AT 6" FROM COMPASS CARD
D 2-7" [X] SPHERES [ ] CYLS AT 12" [X] ATHWARTSHIP [ ] SLEWED - ° [ ] CLOCKWISE [ ] CTR. CLOCKWISE
HEELING MAGNET: [ ] RED UP [X] BLUE UP 6" FROM COMPASS CARD FLINDERS BAR: [X] FORE [ ] AFT 12"
[X] LAT 18°00'N [X] LONG 120°00'E
[ ] H 0.385 [ ] Z 0.151
SIGNED *(Adjuster or Navigator)* APPROVED *(Commanding)*

VERTICAL INDUCTION DATA
(Fill out completely before adjusting)

RECORD DEVIATION ON AT LEAST TWO ADJACENT CARDINAL HEADINGS BEFORE STATING ADJUSTMENT: N 8 W ; E 0 ; S 4 E ; W 9 E .
RECORD BELOW INFORMATION FROM LAST NAVSHIPS 3120/4 DEVIATION TABLE:
DATE 5 December 1974 [ ] LAT 32 53N [ ] LONG 117 18W
[ ] H .260 [ ] Z .420
12" FLINDERS BAR [X] FORWARD [ ] AFT DEVIATIONS N 2.5W E 7E ; S 6.5E W 5W .

RECORD HERE DATA ON RECENT OVERHAULS, GUNFIRE, STRUCTURAL CHANGES, FLASHING, DEPERMING, WITH DATES AND EFFECT ON MAGNETIC COMPASSES

Shipyard overhaul:
3 Oct - 2 Dec 1974
Depermed at Norfolk, Va.:
3 Dec 1974

PERFORMANCE DATA

COMPASS AT SEA: [ ] UNSTEADY [X] STEADY
COMPASS ACTION: [ ] SLOW [X] SATISFACTORY
NORMAL DEVIATIONS: [X] CHANGE [ ] REMAIN RELIABLE
DEGAUSSED DEVIATIONS: [X] VARY [ ] DO NOT VARY

REMARKS

INSTRUCTIONS

1. This form shall be filled out by the Navigator for each magnetic compass as set forth in Chapter 9240 of NAVAL SHIPS TECHNICAL MANUAL.
2. When a swing for deviations is made, the deviations should be recorded both with degaussing coils off and with degaussing coils energized at the proper currents for heading and magnetic zone.
3. Each time this form is filled out after a swing for deviations, a copy shall be submitted to: Naval Ship Engineering Center Hyattsville, Maryland 20782. A letter of transmittal is not required.
4. When choice of box is given, check applicable box.
5. Before adjusting, fill in section on "Vertical Induction Data" above.

NAVSEA 3120/4 (REV. 6-72) (REVERSE) C-[illegible]

Figure 614. Deviation table, NAVSEA 3120/4.

data, as with a new ship, exercise particular care in recording the conventional Daily Compass Log data during the first cruise on which a considerable change of magnetic latitude occurs.

In order to have a reliable and up-to-date deviation card at all times, swing the ship to check compass deviations and to make readjustments, after:

1. Radical changes in magnetic latitude.
2. Deperming. (Delay adjustment for several days after treatment.)
3. Structural changes.
4. Long cruises or docking on the same heading, causing the permanent magnetic condition of the vessels to change.
5. Altering magnetic equipment near the binnacle.
6. Reaching the magnetic equator to acquire Flinders bar data.
7. At least once annually.
8. Changing the heeling magnet position, if Flinders bar is present.
9. Readjusting any corrector.
10. Changing magnetic cargo.
11. Commissioning.

DEVIATION CURVES AND THE ESTIMATION OF APPROXIMATE COEFFICIENTS

615. Simple Analysis

The data for the deviation curve illustrated in Figure 615 is listed below:

	Ship's Compass Heading	*Total Deviation*
N	000 °	10.5 ° E
NE	045 °	20.0 ° E
E	090 °	11.5 ° E
SE	135 °	1.2 ° W
S	180 °	5.5 ° W
SW	225 °	8.0 ° W
W	270 °	12.5 ° W
NW	315 °	6.8 ° W

Since A is the coefficient of constant deviation, its approximate value is obtained from the above data by estimating the mean of the algebraic sum of all the deviations. Throughout these computations the sign of east deviation is considered plus, and west deviation is considered minus.

$8A = +10.5^{\circ}+20.0^{\circ}+11.5^{\circ}-1.2^{\circ}-5.5^{\circ}-8.0^{\circ}-12.5^{\circ}-6.8^{\circ}$
$8A = +42.0^{\circ} - 34.0^{\circ}$
$8A = +8.0^{\circ}$
$A = +1.0^{\circ}$ (1.0° E)

Since B is the coefficient of semicircular sine deviation,

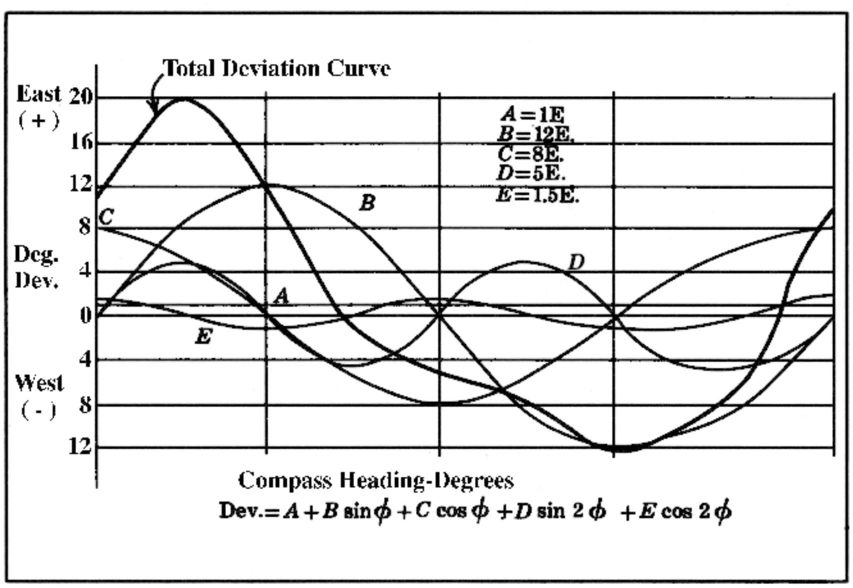


Figure 615. Example of typical deviation curve and its components.

its value is maximum, but of opposite polarity, on 090° and 270° headings. The approximate B coefficient is estimated by taking the mean of the deviations at 090° and 270° with the sign at 270° reversed.

$$2B = +11.5^\circ\ (+12.5^\circ)$$
$$2B = +24.0^\circ$$
$$B = +12.0^\circ\ (12.0^\circ\ E)$$

Similarly, since C is the coefficient of semicircular cosine deviation, its value is maximum, but of opposite polarity, on 000° and 180° headings; and the approximate C coefficient is estimated by taking the mean of the deviations at 000° and 180° with the sign at 180° reversed.

$$2C = +10.5^\circ + (+5.5^\circ)$$
$$2C = +16.0^\circ$$
$$C = +8.0^\circ\ (8.0^\circ\ E)$$

D is the coefficient of quadrantal sine deviation having maximum, but alternately opposite, polarity on the intercardinal headings. Hence, the approximate D coefficient is estimated by taking the mean of the four intercardinal deviations with the signs at 135° and 315° reversed.

$$4D = (+20.0^\circ) + (+1.2^\circ) + (-8.0^\circ) + (+6.8^\circ)$$
$$4D = +20.0^\circ$$
$$D = +5.0^\circ\ (5.0^\circ\ E)$$

E is the coefficient of quadrantal cosine deviation having maximum, but alternately opposite, polarity on the cardinal headings. Therefore, the approximate E coefficient is estimated by taking the mean of the four cardinal deviations with the signs at 090˚ and 270˚ reversed.

$$4E = (+10.5^\circ) + (-11.5^\circ) + (-5.5^\circ) + (+12.5^\circ)$$
$$4E = +6.0^\circ$$
$$E = +1.5^\circ\ (1.5^\circ\ E)$$

These approximate coefficients are estimated from deviations on compass headings rather than on magnetic headings. The arithmetical solution of such coefficients will automatically assign the proper polarity to each coefficient.

Summarizing the above we find the approximate coefficients of the given deviation curve to be:

$$A = 1.0^\circ\ E$$
$$B = 12.0^\circ\ E$$
$$C = 8.0^\circ\ E$$
$$D = 5.0^\circ\ E$$
$$E = 1.5^\circ\ E$$

Each of these coefficients represents a component of deviation which can be plotted as shown in Figure 615. The polarity of each component in the first quadrant must agree with the polarity of the coefficient. A check on the components in Figure 615 will reveal that their summation equals the original curve.

This method of analysis is accurate only when the deviations are less than 20°. The mathematical expression for the deviation on any heading, using the approximate coefficients, is:

$$\text{Deviation} = A + B \sin\theta + C \cos\theta + D \sin 2\theta + E \cos 2\theta$$

(where θ represents compass heading).

The directions given above for calculating coefficients A and B are not based upon accepted *theoretical* methods of estimation. Some cases may exist where appreciable differences may occur in the coefficients as calculated by the above method and the accepted theoretical method. The proper calculation of coefficients B and C is as follows:

Letting D1, D2, . . ., D8 be the eight deviation data, then

$$B = \frac{\sqrt{2}}{8}\left(D_2 + D_4 - D_6 - D_8 + \frac{1}{4}(D_3 - D_7)\right)$$

$$C = \frac{\sqrt{2}}{8}\left(D_2 - D_4 - D_6 + D_8 + \frac{1}{4}(D_1 - D_5)\right)$$

Substituting deviation data algebraically, east being plus and west minus,

$$B = \frac{\sqrt{2}}{8}\left(20.0 - 1.2 - 8.0 - 6.8 + \frac{1}{4}(11.5 - 12.5)\right)$$

$$B = +12$$

$$C = \frac{\sqrt{2}}{8}\left(20.0 - 1.2 - 8.0 + 6.8 + \frac{1}{4}(10.5 - 5.5)\right)$$

$$C = +8$$

This method of estimating approximate coefficients is convenient for:

1. Analyzing an original deviation curve in order to anticipate necessary corrections.
2. Analyzing a final deviation curve for the determination of additional refinements.
3. Simplifying the actual adjustment procedure by anticipating effects of certain corrector changes on the deviations at all other headings.

616. Approximate And Exact Coefficients

The above estimations are for the approximate coefficients and not for exact coefficients. Approximate coefficients are in terms of angular deviations which are caused by certain magnetic forces, and some of these deviations are subject to change with changes in the

directive force, H. The exact coefficients are expressions of magnetic forces, dealing with: (a) arrangements of soft iron, (b) components of permanent magnetic fields, (c) components of the earth's magnetic field, and (d) the shielding factor. Thus, the exact coefficients are expressions of magnetic force which produce the deviations expressed by the approximate coefficients. The exact coefficients are for mathematical considerations while the approximate coefficients are more practical for adjustment purposes. For this reason, the exact coefficients, and the associated mathematics, are not expanded further in this text.

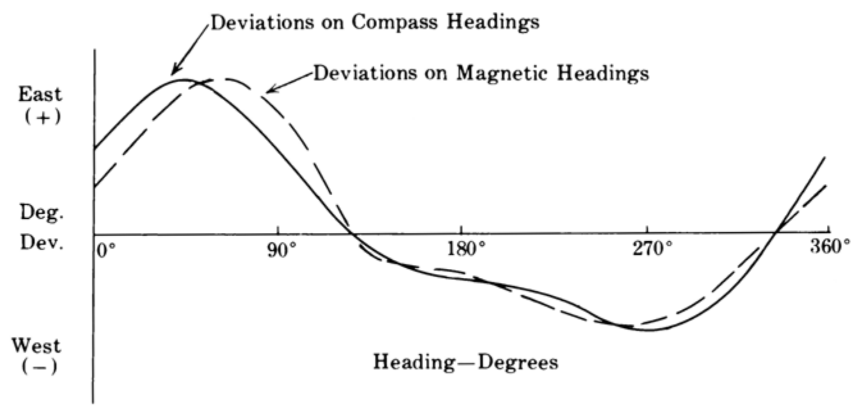


Figure 617. Comparison of deviation curves (magnetic heading versus compass heading).

CORRECTOR EFFECTS

617. Compass Heading And Magnetic Heading

When deviations are large, there is an appreciable difference in the deviation curve if it is plotted on cross-section paper against compass headings or against magnetic headings of the ship. Not only is there a difference in the shape of the curves, but if only one curve is available, navigators will find it difficult in applying deviations when converting between magnetic and compass headings. When deviations are small, no conversion is necessary. Figure 617 illustrates the differences mentioned above by presenting the deviation values used in Figure 617 plotted against both magnetic and compass headings.

618. Understanding Interactions Between Correctors

Until now the principles of compass adjustment have been considered from a qualitative point of view. In general this is quite sufficient since the correctors need merely be moved until the desired amount of correction is obtained. However, it is often valuable to know the quantitative effects of different correctors as well as their qualitative effects. All the correctors are not completely independent of each other. Interaction results from the proximity of the permanent magnet correctors to the soft iron correctors. Consequently any shift in the relative position of the various correctors will change their interactive as well as their separate correction effects. Additional inductions exist in the soft iron correctors from the magnetic needles of the compass itself. The adjuster should be familiar with the nature of these interactions.

619. Quandrantal Sphere Correction

Figure 619 presents the approximate quadrantal correction available with different sizes of spheres, at various positions on the sphere brackets, and with different magnetic moment compasses. These quadrantal corrections apply whether the spheres are used as D, E, or combination D and E correctors. Quadrantal correction from spheres is due partially to the earth's field induction and partially to compass needle induction. Since compass needle induction does not change with magnetic latitude but earth's field induction does, the sphere correction is not constant for all magnetic latitudes. A reduction in the percentage of needle induction in the spheres to the earth's field induction in the spheres will improve the constancy of sphere correction over all magnetic latitudes. Such a reduction in the percentage of needle induction may be obtained by:

1. Utilizing a low magnetic moment compass.
2. Utilizing special spheroidal-shaped correctors,

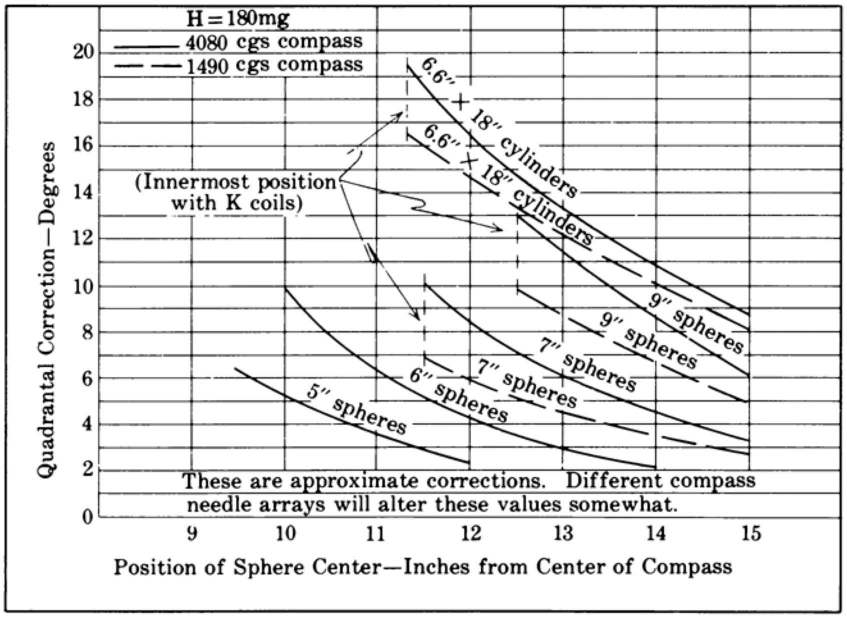


Figure 619. Quandrantal correction curves.

placed with their major axes perpendicular to their axis of position.

3. Using larger spheres farther away from the compass.

620. Slewing Of Spheres

Figure 620 shows a chart for determining the proper slewed position for spheres. The total values of the D and E quadrantal coefficients are used on the chart to locate a point of intersection. This point directly locates the angle and direction of slew for the spheres on the illustrated binnacle. This point will also indicate, on the radial scale, the resultant amount of quadrantal correction required from the spheres in the new slewed position to correct for both D and E coefficients. The total D and E coefficients may be calculated by an analysis of deviations on the uncorrected binnacle, or by summarizing the uncorrected coefficients with those already corrected. The data in Figure 619 and 622 will be useful in either procedure.

Example: A ship having a Navy Standard binnacle, with 7" spheres at 13" position athwartship, and a 12" Flinders bar forward, is being swung for adjustment. It is observed that 4° E D error and 6° E E error exist with the spheres in position. Since the spheres are athwartship, the

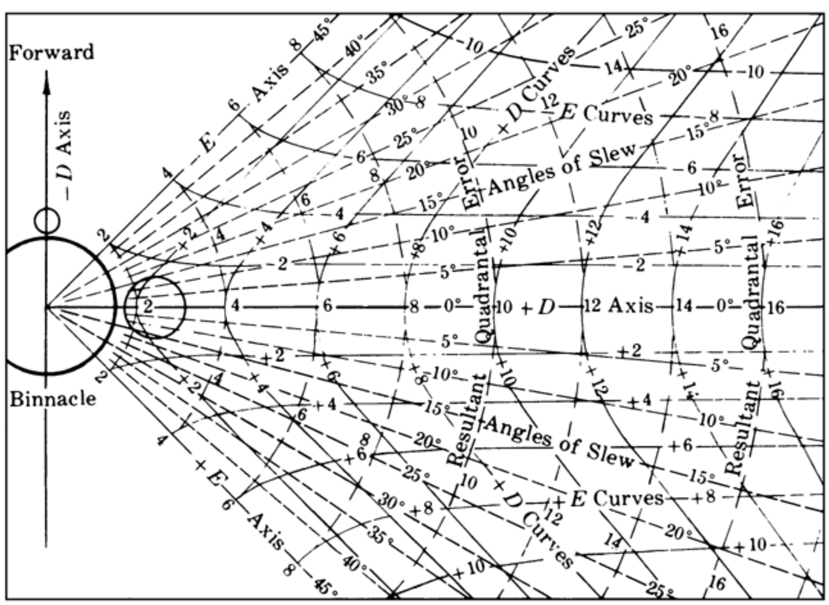


Figure 620. Slewing of quandrantal spheres.

total E coefficient for the ship is 6° E, as observed. Figure 619 indicates that the spheres in their present position are correcting 6° E D error, hence the total D coefficient of the ship and Flinders bar is 10° E. Figure 620 indicates that 6° E E and 10° E D coefficients require slewing the spheres 15.5° clockwise from their present athwartship position. The resultant quadrantal error is indicated as 11.7°. Figure 619 indicates that the 7" spheres should then be moved to the 11" position after slewing 15.5° clockwise so as to correct both the D and E errors. Using this chart eliminates trial-and-error adjustment methods for quadrantal errors and provides information for moving the spheres.

621. Corrector Magnet Inductions In Spheres

Should a ship have both spheres and many permanent B and C magnet correctors close to the compass, induction will exist between these correctors. This induction will require some shuttling back and forth between headings while making adjustments. This situation can be improved by using larger spheres further out, by approximately setting the spheres before starting adjustments, and by using more magnets further from the spheres and compass. Magnetized spheres Flinders bars will cause difficulty during adjustment, and introduce an unstable deviation curve if they suffer a change of magnetic condition.

622. Flinders Bar Effects

Figure 622 presents the approximate quadrantal error introduced by the presence of the Standard Navy Flinders bar. Since the Flinders bar is usually placed in the forward or aft position, it acts as a small minus D corrector as well as a corrector for vertical induced effects. This means that when inserting the Flinders bar, move the regular spheres closer to correct for the increased plus D error. Conversely, move the regular spheres away when removing the Flinders bar. This D error in the Flinders bar is due mostly to compass needle induction because the bar is small in cross-section and close to the compass. Such needle induction is practically constant; therefore, the deviation effects on the compass will change with magnetic latitudes because the directive force, H, changes. However, when balanced by sphere correctors, this effect tends to cancel out the variable part of the sphere correction caused by the compass needle induction.

623. Flinders Bar Adjustment

One must have reliable data obtained in two widely separated magnetic latitudes to place the correct amount of Flinders bar. Placing the Flinders bar by any other method is merely an approximation. Obtaining the required magnetic data will necessitate further refinements. There are several methods of acquiring and using latitude data in order to determine the proper amount of Flinders bar:

The data required for correct Flinders bar adjustment consists of accurate tables of deviations with details of corrector conditions at two different magnetic latitudes; the farther apart the better. Should it be impossible to swing ship for a complete table of deviations, the deviations on east and west magnetic headings would be helpful. Ship's log data is usually not reliable enough for Flinders bar calculation. Observe the following precautions when taking data. These precautions will ensure that deviation changes are due only to changes in the H and Z components of the earth's field.

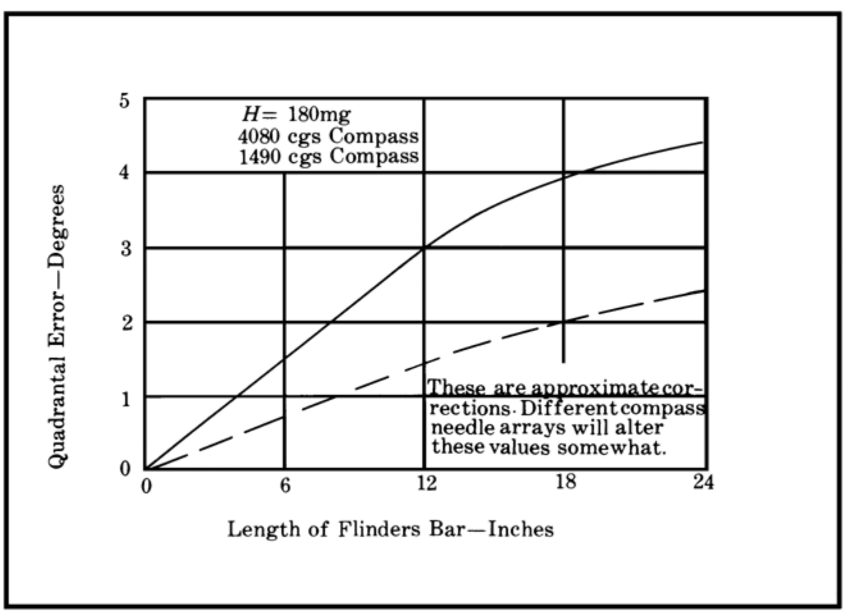


Figure 622. Quadrantal error from standard Navy Flinders bar.

1. Degaussing should be secured, by a reversal process if necessary, at both latitudes before data are taken.

2. If the ship has been in dock or steaming, on one heading for several days prior to the taking of these data, the resulting temporary magnetism (Gaussin error) would create erroneous deviations. A shakedown on other headings prior to taking data will reduce such errors.

3. Any major change in the ship's magnetic field (caused, for example, by deperming, structural changes, heavy gunfire, shifting magnetic cargoes) between data sets will make the comparative results meaningless.

4. Because the data will not be reliable if the ship's permanent magnetism changes between the two latitudes, it will likewise be unreliable if any of the binnacle correctors are changed.

In the event that an approximation as to Flinders bar length cannot be made, then the deviations at the two latitudes should be taken with no Flinders bar in the holder. This procedure would also simplify the resulting calculations.

624. Methods Of Determining Flinders Bar Length

Method 1. Having obtained reliable deviation data at two different magnetic latitudes, the changes in the deviations, if any, may justifiably be attributed to an incorrect Flinders bar adjustment. E/W and N/S deviations are the ones which are subject to major changes from such an incorrect adjustment. If there is no change in any of these deviations, the Flinders bar adjustment is probably correct. A change in the E/W deviations indicates an unsymmetrical arrangement of vertical iron forward or aft of the compass, which requires correction by the Flinders bar, forward or aft of the compass. A change in the N/S deviations indicates an unsymmetrical arrangement of vertical iron to port or starboard of the compass, which requires correction by the Flinders bar to port or starboard of the compass. This latter case is very rare, but can be corrected.

Determine the B deviations on magnetic east/west headings at both latitudes. The constant c may then be calculated from the following formula:

$$c = \lambda \frac{H_1 \tan B_1 - H_2 \tan B_2}{Z_1 - Z_2}$$

where

λ = shielding factor (0.7 to 1.0 average).
H_1 = earth's field, H, at 1st latitude.
B_1 = degrees B deviation at 1st latitude (magnetic headings).
Z_1 = earth's field, Z, at 1st latitude.
H_2 = earth's field, H, at 2nd latitude.
B_2 = degrees B deviation at 2nd latitude (magnetic headings).
Z_2 = earth's field, Z, at 2nd latitude.

This constant c represents a resultant mass of vertical iron in the ship which requires Flinders bar correction. If the Flinders bar is present at the time of calculations, it must be remembered that it is already correcting an amount of c in the ship which must be added to the uncorrected c, calculated by the above formula. This total value of c is used in conjunction with Figure 624a to indicate, directly, the necessary total amount of Flinders bar. If this total c is negative, Flinders bar is required on the forward side of the binnacle; and if it is positive, a Flinders bar is required on the aft side of the binnacle. The iron sections of Flinders bar should be continuous and at the top of the tube with the longest section at the top. Wooden spacers are used at the bottom of the tube. It will be noted that the B deviations used in this formula are based on data on E/W magnetic headings rather than on compass headings, as with the approximate coefficients.

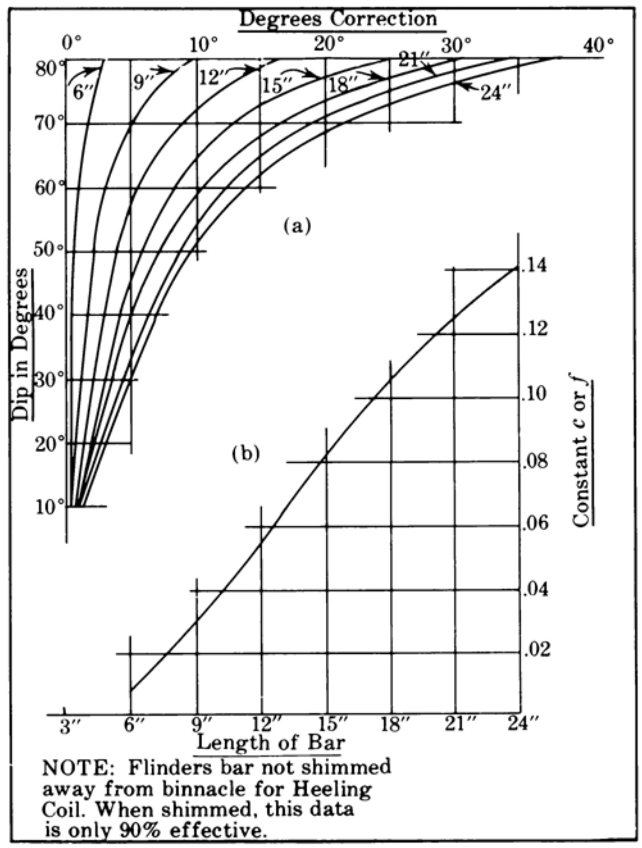


Figure 624a. Dip deviation curves for Flinders bar.

Method 2. Should the exact amount of correction required for vertical induction in the ship at some particular

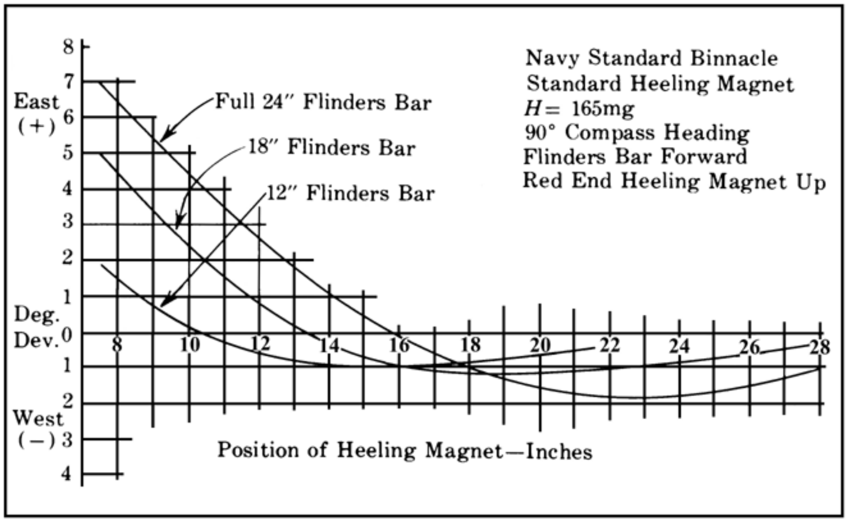


Figure 624b. Induction effects in Flinders bar due to heeling.

magnetic dip, q, be known, Figure 624a will directly indicate the correct amount of Flinders bar to be placed at the top of the holder. The exact amount of correction would be known when one of the latitudes is the magnetic equator, and the deviations there are negligible. Then the B deviation, in degrees, on magnetic headings at the other latitude, is the exact amount to correct by means of curves in Figure 624a.

Method 3. Lord Kelvin's rule for improving the Flinders bar setting is: "Correct the deviations observed on east or west courses by the use of fore-and-aft B magnets when the ship has arrived at places of weaker vertical magnetic field, and by the use of Flinders bar when she has arrived at places of stronger vertical magnetic field, whether in the Northern or Southern Hemisphere."

After determining the correct amount of Flinders bar, by either method (1) or (2) above, the bar should then be inserted at the top of the holder, and the fore-and-aft B magnets readjusted to correct the remaining B error. Sphere adjustments should likewise be refined.

It is quite possible that on inserting the Flinders bar, no visible deflection of the compass will be observed, even on an east or west heading. This should cause no concern because certain additional induction effects exist in the bar, from:

1. The heeling magnet.
2. The existing fore-and-aft magnets.
3. The vertical component of the ship's permanent magnetic field.

Figure 624b presents typical induction effects in the Flinders bar for different positions of heeling magnet. An adjuster familiar with the nature of these effects will appreciate the advantages of establishing the Flinders bar and heeling magnet combination before leaving dockside. Deviations must also be checked after adjusting the heeling magnet, if Flinders bar is present.

625. Slewing Of Flinders Bar

The need for slewing the Flinders bar is much more rare than that for slewing spheres. Also, the data necessary for slewing the Flinders bar cannot be obtained on a single latitude adjustment, as with the spheres. Slewing the bar to some intermediate position is, in effect, merely using one bar to do the work of two; one forward or aft, and the other port or starboard.

Section 624 explains that a change of the E/W deviations, with changes in latitude, indicates the need for Flinders bar forward or aft of the compass; and a change of the N/S deviations, with changes in latitude, indicates the need for Flinders bar to port or starboard of the compass.

A change of the B deviations on magnetic E/W headings is used, as explained in section 624, to determine the proper amount of Flinders bar forward or aft of the compass, by calculating the constant c.

If there is a change of the C deviations on magnetic N/S headings, a similar analysis may be made to determine the proper amount of Flinders bar to port or starboard of the compass by calculating the constant f from:

$$f = \lambda \frac{H_1 \tan C_1 - H_2 \tan C_2}{Z_1 - Z_2}$$

when

λ = shielding factor (0.7 to 1.0 average).

H_1 = earth's field, H, at 1st latitude.
C_1 = degrees C deviation at 1st latitude (magnetic headings).
Z_1 = earth's field, H, at 1st latitude.
H_2 = earth's field, H, at 2nd latitude.
C_2 = degrees C deviation at 2nd latitude (magnetic headings).
Z_2 = earth's field, Z, at 2nd latitude.

Any value of this *f* constant indicates the need for Flinders bar adjustment athwartship of the compass, just as a value of the c constant indicates the need for Flinders bar adjustment forward or aft of the compass. The *f* constant curve in Figure 624b is used for the determination of this Flinders bar length. If *f* is negative, Flinders bar is required on the starboard side of the binnacle.

Should both c and f exist on a ship, the angular position for a Flinders bar to correct the resultant vertical induction effects may be found by:

$$\tan\beta = \frac{f}{c} \quad \text{or} \quad \beta = \tan^{-1}\frac{f}{c}$$

β is the angle to slew the Flinders bar from the fore-and-aft axis. If *c* and *f* are negative, the bar will be slewed clockwise from the forward position; if *c* is negative and *f* is positive, the bar will be slewed counterclockwise from the aft position.

After determining the angle to slew the Flinders bar from the fore-and-aft line, the total amount of Flinders bar necessary to correct the resultant vertical induction effects in this position is found by:

$$r = \sqrt{c^2 + f^2}$$

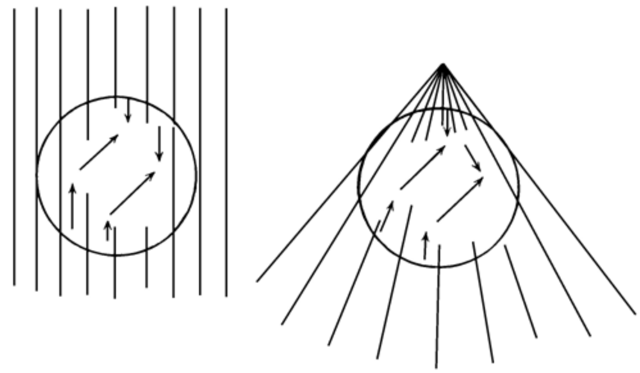


Figure 626a. Magnetic fields across compass needle arrays.

The constant *r* is then used on the *c* or *f* constant curve in Figure 624b to determine the total amount of Flinders bar necessary in the slewed position.

626. Compasses

Compasses themselves play a very important part in compass adjustment, although it is common belief that the compass is only an indicating instrument, aligning itself in the resultant magnetic field. This would be essentially true if the magnetic fields were uniform about the compass; but, unfortunately, magnetism close to the compass imposes nonuniform fields across the needles. In other words, adjustment and compensation sometimes employ non-uniform

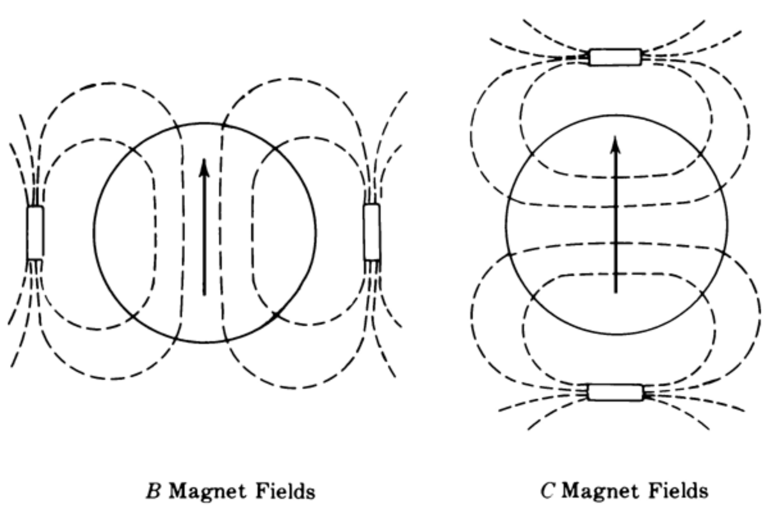


Figure 626b. Arrangements of corrector magnets.

fields to correct uniform fields. Figure 626a indicates the difference between uniform and nonuniform field effects on a compass. Such unbalanced torques, arising from nonuniform magnetic fields, create deviations of the compass which have higher frequency characteristics. Compass designs include many combinations of different length needles, different numbers of needles, and different spacings and arrangements of needles all designed to minimize the higher order deviations resulting from such nonuniform magnetic fields. Although compass design is rather successful in minimizing such deviations, it is obvious that different compasses will be affected differently by the same magnetic fields. It is further stressed that, even with proper compass design, it is the responsibility of all adjusters to exercise care in applying correctors, in order to create the most uniform magnetic field possible.

This is the basis for the rule which requires the use of strong correctors symmetrically arranged, as far away from the compass as possible, instead of weak correctors very close to the compass. In general it is better to use larger spheres placed at the extremities of the brackets, equally distant from the center of the compass. B and C permanent magnet correctors should always be placed so as to have an equal number of magnets on both sides of the compass where possible. They should also be centered as indicated in Figure 626b, if regular tray arrangements are not available. The desire for symmetrical magnetic fields is one reason for maintaining a sphere of specified radius, commonly called the **magnetic circle**, about the magnetic compass location. This circle is kept free of any magnetic or electrical equipment.

The **magnetic moment** of the compass needle array, another factor in compass design, ranks in importance with the proper arrangement of needles. This magnetic moment controls the needle induction in the soft iron correctors, as discussed in section 619 and section 622, and hence governs the constancy of those corrector effects with changes in magnetic latitude. The $7^1/_2$" Navy No. 1 alcohol-water compass has a magnetic moment of approximately 4000 cgs units, whereas the $7^1/_2$" Navy No. 1 oil compass has a magnetic moment of approximately 1650 cgs units. The lower magnetic moment compass allows considerably less change in quadrantal correction, although the periods are essentially comparable, because of the difference in the compass fluid characteristics.

Other factors which must be considered in compass design are period, fluid, swirl, vibration, illumination, tilt, pivot friction, fluid expansion, and others. These factors, however, are less important from an adjuster’s point of view than the magnetic moment and arrangement of needles, and are therefore not discussed further in this text.

SHIP’S HEADING

627. Ship’s Heading

Ship’s heading is the angle, expressed in degrees clockwise from north, of the ship’s fore-and-aft line with respect to the true meridian or the magnetic meridian. When this angle is referred to the true meridian, it is called a **true heading**. When this angle is referred to the magnetic meridian, it is called a **magnetic heading**. Heading, as indicated on a particular compass, is termed the ship’s compass heading by that compass. It is always *essential* to specify heading as true heading, magnetic heading, or compass heading. In order to obtain the heading of a ship, it is essential that the line through the pivot and the forward lubber’s line of the compass be parallel to the fore-and-aft line of the ship. This applies also to the peloruses and gyro repeaters, which are used for observational purposes.

628. Variation And Deviation

Variation is the angle between the magnetic meridian and the true meridian at a given location. If the northerly part of the magnetic meridian lies to the right of the true meridian, the variation is easterly, and if this part is to the left of the true meridian, the variation is westerly. The local variation and its small **annual change** are noted on the compass rose of all navigational charts. Thus the true and magnetic headings of a ship differ by the local variation. Chart 42 shows approximate variation values for the world.

As previously explained, a ship’s magnetic influence will generally cause the compass needle to deflect from the magnetic meridian. This angle of deflection is called **deviation**. If the north end of the needle points east of the magnetic meridian, the deviation is easterly; if it points west of the magnetic meridian, the deviation is westerly.

629. Heading Relationships

A summary of heading relationships follows:

1. **Deviation** is the difference between the compass heading and the magnetic heading.
2. **Variation** is the difference between the magnetic heading and the true heading.
3. The algebraic sum of deviation and variation is the **compass error**.

Figure 629 illustrates these relationships. The following simple rules will assist in naming errors and in converting from one heading to another:

1. Compass least, deviation east, compass best, deviation west.
2. When correcting, add easterly errors, subtract westerly errors.
3. When uncorrecting, subtract easterly errors, add westerly errors.

Typical heading relationships are as follows:

Compass	Deviation	Magnetic	Variation	True
358°	5°E	003°	6°E	009°
120°	1°W	119°	3°E	122°
180°	6°E	186°	8°W	178°
240°	5°W	235°	7°W	228°

Figure 629. Magnetic heading relationships.

Use the memory aid "Can Dead Men Vote Twice at Elections" to remember the conversion process (Compass, Deviation, Magnetic, Variation, True, add east). When converting Compass Heading to True Heading, add east deviations and variations and subtract west deviations and variations.

Complete facility with conversion of heading data is essential for expeditious compass adjustment.

630. Use Of Compass Heading And Magnetic Heading For Adjustment

The primary object of adjusting compasses is to reduce deviations; that is, to minimize the difference between the magnetic and compass headings. There are two methods for accomplishing this:

Method 1. Place the ship on the desired magnetic heading (section 631) and correct the compass so that it reads the same as this magnetic heading. This is the preferred method.

Method 2. Place the ship on the desired compass heading and determine the corresponding magnetic heading of the ship. Correct the compass so that it reads the same as this known magnetic heading. Use this method whenever it is impractical to place the ship on a steady magnetic heading for direct correction.

One can easily observe compass deviation when using the first method because it is simply the difference between the compass reading and the known magnetic heading of the ship. The difficulty in using this method lies in placing the ship on the desired magnetic heading and holding the ship steady on that heading while adjustments are being made.

The difficulty in using the second method lies in the determining deviation. Further difficulty arises because the

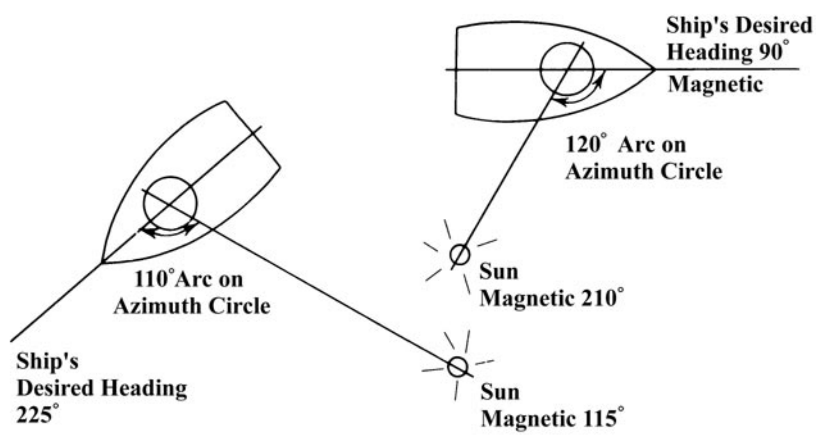


Figure 630. Azimuth circle set-ups.

helmsman steers by an uncorrected compass whose deviations are changing while the technician is making the necessary adjustments. Therefore, as each adjustment is being made, the helmsman should hold the ship's heading steady by some means other than the compass that is being corrected.

If the compass has no appreciable deviation, the deviation taken on compass headings will closely approximate those taken on magnetic headings. However, as the magnitude of errors increases, there will be a marked difference between the deviations taken on compass headings and those taken on magnetic headings.

631. Methods Of Placing Ship On Magnetic Headings

Method 1. Bring the ship onto a magnetic heading by referencing a gyrocompass. The magnetic variation applied to true heading determines the gyro course to be steered to place the ship on the required magnetic heading. Take gyrocompass error into consideration in determining gyro course to be steered.

The difference between gyro heading and magnetic heading will be constant on all headings as long as the gyrocompass error is constant and the variation does not change. Determine gyrocompass error by comparing the calculated true azimuth of the sun and the azimuth as observed on a synchronized repeater.

It should be remembered that gyrocompasses have certain errors resulting from latitude and speed changes, and these errors are not always constant on all headings. For these reasons, the gyro error must be checked constantly, especially if the gyro is being used to obtain data for determining residual deviation curves of the magnetic compass.

Method 2. Place the ship on a magnetic heading by aligning the vanes of an azimuth circle with the sun over the topside compass. The sun is a distant object whose azimuth (angle from the north) may be computed for any given time. Methods of calculating sun's azimuths are discussed in the next section. By setting the line of sight of the vanes at an angle to the right (or left) of the fore-and-aft line of the ship equal to the difference between the computed magnetic azimuth and the desired magnetic heading of the ship, and then swinging the ship until the sun is aligned with the vanes, the ship will be on the desired magnetic heading. Simple diagrams with the ship and sun drawn in their relative positions, will aid in visualizing each problem. Always keep the azimuth circle level while making observations. This holds especially true for observing celestial bodies.

Method 3. Use a distant object (10 or more miles away) with the azimuth circle when placing the ship on magnetic headings. This procedure is similar to that used with the sun except that the magnetic bearing of the object is constant. With an object 11.4 nautical miles distant, a change in position of 400 yards at right angles to the line of sight introduces an error of 1°.

Method 4. Use a pelorus to place a ship on a magnetic heading using the sun's azimuth in much the same manner as with the azimuth circle. Using the pelorus allows the magnetic heading of the ship to be observed continuously as the ship swings. Clamp the forward sight vane to the dial at the value of the sun's magnetic azimuth. Then, train the sight vanes so that the sun is reflected in the mirror. As the ship turns, observe the magnetic heading under the forward lubber's line. As the desired magnetic course is approached, the compass can be read and corrected even before that magnetic course is actually obtained. A final check can be made when the ship is on the exact course. Always keep the pelorus level while making observations, particularly of celestial bodies.

Method 5. A distant object can be used in conjunction with the pelorus, as with the azimuth circle, in order to place the ship on magnetic headings.

632. Methods Of Determining Deviations On Compass Heading

Method 1. Determine the compass' deviation by comparing the sun's calculated magnetic azimuth to the azimuth observed using an azimuth circle. The next section discusses methods of calculating the sun's azimuths. Place the ship on the desired compass heading and take an azimuth of the sun on the compass card's face. The difference between the observed azimuth and the calculated magnetic azimuth of the sun is the deviation on that compass course.

Method 2. Use the pelorus with the sun's azimuth to obtain deviations on compass headings. Bring the ship to the desired compass heading and set the forward sight vane on the value calculated for the sun's magnetic azimuth. Then train the sight vanes on the sun. The pelorus indicates the ship's magnetic heading. The difference in degrees between the compass heading and magnetic heading of the ship indicated by the pelorus is the deviation on that compass course.

Method 3. Use the azimuth circle or pelorus in conjunction with ranges or a distant object to obtain deviations on compass courses. The procedure is similar to that used with the sun. A range consists of any two objects or markers, one in the foreground and the other in the background, which establishes a line of sight having a known magnetic bearing. Determine the range's true bearing from a chart; then, convert this true bearing to the magnetic bearing by applying the variation listed on the chart. Bring the ship to the desired compass course and, at the instant of crossing the line of sight of the range, take a bearing to the range. With the azimuth circle, the difference between the observed range bearing and the known magnetic range bearing represents the deviation on that compass course. If using a pelorus, set the forward sight vanes to the magnetic bearing of the range and read the ship's magnetic heading when taking a sight on the range. The deviation is the difference between the compass heading of the ship and the known

magnetic heading of the ship as indicated by pelorus.

Method 4. Obtain deviations on compass courses by using reciprocal bearings. Set up a pelorus on shore and align the dial's south end with magnetic north. A ship then sights the pelorus on shore, using an azimuth circle or pelorus, at the same instant the observer on shore sights the ship. The ship's bearing from shore on the reversed pelorus is the magnetic bearing of the shore position from the ship. Continuous communication between ship and shore is necessary when employing this method.

Additional methods of determining deviations are by the use of azimuths of the moon, stars, and planets.

AZIMUTHS

633. Azimuths Of The Sun

The sun is a valuable reference point for compass adjustment because one can easily obtain accurate compass bearings of the sun and compare these bearings with the sun's calculated true bearing (azimuth) to obtain compass error. One can use the azimuths of other celestial bodies to make this comparison; however, none are as convenient as the sun.

Calculating an azimuth of the sun is covered in Chapter 17.

634. Curve Of Magnetic Azimuths

During the course of compass adjustment and swinging ship, a magnetic direction is needed many times, either to place the vessel on desired magnetic headings or to determine the deviation of the compass being adjusted. The sun's azimuth continually changes as the earth rotates. Compensate for this by preparing a **curve of magnetic azimuths**. Compute true azimuths at frequent intervals. Then, apply the variation at the center of the maneuvering area to determine the equivalent magnetic azimuths. Plot the magnetic azimuths versus time and fair a curve through the points. Plotting at least three points at intervals of half an hour is usually sufficient. If the sun is near the celestial meridian and relatively high in the sky, plot additional points.

Unless extreme accuracy is required, determine the Greenwich hour angle and declination for the approximate midtime. Additionally, use the same declination for all computations. Assume the Greenwich hour angle increase at 15° per hour.

TRANSIENT DEVIATIONS OF THE MAGNETIC COMPASS

635. Stability

So far this chapter has discussed only the principles of steady-state magnetism. However, a carefully made correction based on these steady-state phenomenon may turn out to be inaccurate due to transient magnetic effects. A compass adjuster cannot place correctors on the binnacle for such variable effects; he must recognize and handle them in the best possible manner. A good adjuster not only provides an accurate deviation curve which is reliable under steady state conditions, but he also records transient magnetic effects which cannot be eliminated.

636. Sources Of Transient Error

The magnetic circle about the magnetic compass is intended to reduce any transient conditions, but there still are many items which cause the compass to act erratically. The following is a list of some such items. If in doubt about the effect of an item on compass performance, a test can be made by swinging any movable object or energizing any electrical unit while observing the compass for deviations. This would best be tried on two different headings 90° apart, since the compass might possibly be affected on one heading and not on another.

Some magnetic items which cause variable deviations if placed too close to the compass are as follows:

1. Guns on movable mounts.
2. Ready ammunition boxes.
3. Variable quantities of ammunition in ready boxes.
4. Magnetic cargo.
5. Hoisting booms.
6. Cable reels.
7. Metal doors in wheelhouse.
8. Chart table drawers.
9. Movable gyro repeater.
10. Windows and ports.
11. Signal pistols racked near compass.
12. Sound powered telephones.
13. Magnetic wheel or rudder mechanism.
14. Knives or tools near binnacle.
15. Watches, wrist bands, spectacle frames.
16. Hat grommets, belt buckles, metal pencils.
17. Heating of smoke stack, or exhaust pipes.
18. Landing boats.

Some electrical items which cause variable deviations if placed too close to the compass are:

1. Electric motors.
2. Magnetic controllers.
3. Gyro repeaters.
4. Nonmarried conductors.
5. Loudspeakers.
6. Electric indicators.
7. Electric welding.
8. Large power circuits.
9. Searchlights.
10. Electrical control panels or switches.
11. Telephone headsets.
12. Windshield wipers.
13. Rudder position indicators, solenoid type.
14. Minesweeping power circuits.
15. Engine order telegraphs.
16. Radar equipment.
17. Magnetically controlled switches.
18. Radio transmitters.
19. Radio receivers.
20. Voltage regulators.

Another source of transient deviation is the **retentive error**. This error results from the tendency of a ship's structure to retain some of the induced magnetic effects for short periods of time. For example, a ship traveling north for several days, especially if pounding in heavy seas, will tend to retain some fore-and-aft magnetism hammered in under these induction conditions. Although this effect is transient, it may cause incorrect observations or adjustments. This same type of error occurs when ships are docked on one heading for long periods of time. A short shakedown, with the ship on other headings, will tend to remove such errors. A similar sort of residual magnetism is left in many ships if the degaussing circuits are not secured by the reversal sequence.

A source of transient deviation trouble shorter in duration than retentive error is known as **Gaussin error**. This error is caused by eddy currents set up by a changing number of magnetic lines of force through soft iron as the ship changes heading. Due to these eddy currents, the induced magnetism on a given heading does not arrive at its normal value until about 2 minutes after changing to the heading.

Deperming and other magnetic treatment will change the magnetic condition of the vessel and therefore require compass readjustment. The decaying effects of deperming are sometimes very rapid. Therefore, it is best to delay readjustment for several days after such treatment. Since the magnetic fields used for such treatments are sometimes rather large at the compass locations, the Flinders bar, compass, and related equipment are sometimes removed from the ship during these operations.

HEELING ADJUSTMENTS

637. Use Of The Dip Needle In Heeling Adjustments

The heeling effects of both the permanent and induced magnetism are corrected by adjusting the position of the vertical permanent heeling magnet. This adjustment can be made in either of two ways:

Method 1. With the ship on an even keel and as close to the east or west magnetic heading as possible, adjust the heeling magnet until a dip needle inserted in the compass position is balanced at some predetermined position.

Method 2. Adjust the heeling magnet, while the ship is rolling on north and south headings, until the oscillations of the compass card have been reduced to an average minimum.

To establish an induction condition between the heeling magnet and Flinders bar and to minimize heeling oscillations before at-sea adjustments, set the heeling magnet at dockside by the first method above. Further, position the Flinders bar and spheres before making any heeling adjustments because of the heeling correction and shielding effect they produce.

Readjust the heeling magnet when the ship changes magnetic latitude appreciably because the heeling magnet corrects for induced as well as permanent magnetic effects. Moving the heeling magnet with Flinders bar in the holder will change the induction effects in the Flinders bar and consequently change the compass deviations. Thus, the navigator is responsible for:

1. Moving the heeling magnet up or down (invert when necessary) as the ship changes magnetic latitude, to maintain a good heeling adjustment for all latitudes.

2. Checking his deviations and noting changes resulting from movements of the heeling magnet when Flinders bar is in the holder. Any deviation changes should be either recorded or readjusted by means of the fore-and-aft B magnets.

There are two types of dip needles. One assumes the angle of inclination for its particular location, and one uses a moveable weight to balance any magnetic torque. The latter type renders the needle's final position more independent of the horizontal component of magnetic fields. It, therefore, is more useful on uncorrected compasses.

For ships with no shielding of the earth's field at the compass (having no surrounding metal structure), the procedure for adjusting the heeling magnet is quite simple. Take the dip needle to a nearby area where there is no local magnetic attraction, level the instrument, and set the weight to balance the needle. It is preferable to align the instrument so that the north seeking end of the needle is pointing north. Next, level the instrument in the compass position on board ship, place the spheres in their approximate position, and adjust the heeling magnet until the needle assumes the balanced condition. This presumes that all the effects of the ship are canceled, leaving only the effect of the vertical earth's field. Secure the degaussing circuits during this adjustment.

Some ships have shielding effects at the compass. Such would be the case for a metal enclosed wheelhouses. In this case, the procedure is essentially the same as above except that the weight on the dip needle should be moved toward the pivot to balance against some lesser value of earth's field. The new position of the weight, expressed in centimeters from the pivot, can be approximately determined by multiplying the value of lambda, λ, for the compass location by the original distance of the weight from the pivot in centimeters. Should λ, for the compass location be unknown, it may generally be considered as about 0.8 for steering compass locations and 0.9 for standard compass locations. By either method, the weight on the dip needle should be moved into its new position. Next, level the instrument in the compass position on board ship and adjust the heeling magnet until the needle assumes the balanced condition.

Theoretically, these methods of adjusting the heeling magnet with a dip needle should be employed only with the ship on east or west magnetic headings. This avoids heeling errors resulting from unsymmetrical induced magnetism. If it is impractical to place the ship on such a heading, make approximations on any heading and refine these approximations when convenient.

To summarize, a successful heeling magnet adjustment is one which minimizes the compass oscillations caused by the ship's rolling. Therefore, the rolling method is a visual method of adjusting the heeling magnet or checking the accuracy of the last heeling magnet adjustment. Generally, the oscillation effects due to roll on both the north and south compass headings will be the same. However, some unsymmetrical arrangements of fore-and-aft soft iron will introduce different oscillation effects on these two headings. Such effects cannot be entirely eliminated on both headings with one setting of the heeling magnet. Therefore, the heeling magnet is generally set for the average minimum oscillation condition.

USE OF THE HORIZONTAL FORCE INSTRUMENT

638. Determining The Horizontal Shielding Factor

Occasionally, the navigator must determine the magnetic field strength at some compass location for one of the following reasons:

1. To determine the horizontal shielding factor, lambda (λ), for:
    a. A complete mathematical analysis.
    b. Accurate Flinders bar adjustment.
    c. Accurate heeling adjustment.
    d. Calculations on a dockside magnetic adjustment.
    e. Determining the best compass location on board ship.
2. To make a dockside magnetic adjustment for determining the magnitude and direction of the existing directive force at the magnetic compass.

The **horizontal shielding factor** is the ratio of the reduced earth's directive force, H', on the compass to the horizontal earth's field, H.

$$\lambda = \frac{H'}{H}$$

The navigator can determine λ for a compass location by making a measurement of the reduced earth's directive force, H'. On a corrected compass, this value H' may be measured with the ship on any heading, since this reduced earth's directive force is the only force acting on the compass. If the compass is not corrected for the ship's magnetism and the deviations are large, H' is determined from the several resultant directive forces observed with equally spaced headings of the ship. The Horizontal Shielding Factor should be determined for every compass location on every ship.

639. Measurement Of Magnetic Fields

Use a suitable **magnetometer** or a **horizontal force instrument** to measure magnetic fields. The magnetometer method is a direct reading method requiring no calculation. However, the force instrument method requires much less complicated test equipment so this method is discussed below.

The horizontal force instrument is simply a magnetized needle pivoted in a horizontal plane, much the same as a compass. It will settle in some position which will indicate the direction of the resultant magnetic field. Determine the resulting field's strength by comparing it with a known field. If the force needle is started swinging, it will be damped down with a certain period of oscillation dependent upon the strength of the surrounding magnetic field. The stronger the magnetic field, the shorter the period of time for each cycle of swing. The ratio is such that the squares of the period of vibration are inversely proportional to the strengths of the magnetic fields. This relationship is expressed as follows:

$$\frac{H'}{H} = \frac{T^2}{T'^2}$$

In the above formula, let H represent the strength of the earth's horizontal field in gauss and T represent the time in seconds for 10 cycles of needle vibration in that earth's field. A comparative measurement of time in seconds, T', for 10 cycles of vibration of the same needle in the unknown field will enable the navigator to calculate H'.

Since λ is the ratio of two magnetic field strengths, it may be found directly by the inverse ratio of the squares of the periods of vibration for the same horizontal force instrument in the two different magnetic fields by the same formula, without bothering about the values of H and H'.

The above may be used on one heading of the ship if the compass deviations are less than 4°.

$$\lambda = \frac{H'}{H} = \frac{T^2}{T'^2}$$

Use the following equation to obtain a more precise value of λ, and where compass deviations exceed 4°:

$$\lambda = \frac{T^2}{4}\left[\frac{\cos d_n}{T^2{}_n} + \frac{\cos d_e}{T^2{}_e} + \frac{\cos d_s}{T^2{}_s} + \frac{\cos d_w}{T^2{}_w}\right]$$

where:

T is the time period for the field H.

T_n is the time period for the resultant field on a north heading, etc.

cos d_n is the cos of the deviation on the north heading, etc.

DEGAUSSING (MAGNETIC SILENCING) COMPENSATION

640. Degaussing

A steel vessel has a certain amount of **permanent magnetism** in its "hard" iron and **induced magnetism** in its "soft" iron. Whenever two or more magnetic fields occupy the same space, the total field is the vector sum of the individual fields. Thus, near the magnetic field of a vessel, the total field is the combined total of the earth's field and the vessel's field. Therefore, the earth's magnetic field is altered slightly by the vessel.

Since certain mines are triggered by a vessel's magnetic influence of a vessel passing near them, a vessel tries to minimize its magnetic field. One method of doing this is to neutralize each component of the field with an opposite electromagnetic field produced by electric cables coiled around the vessel. These cables, when energized, counteract the permanent magnetism of the vessel, rendering it magnetically neutral. This obviously has severe effects on magnetic compasses.

A unit sometimes used for measuring the strength of a magnetic field is the **gauss**. Reducing of the strength of a magnetic field decreases the number of gauss in that field. Hence, the process is called **degaussing**.

When a vessel's degaussing coils are energized, the magnetic field of the vessel is completely altered. This introduces large deviations in the magnetic compasses. This is removed by introducing at the magnetic compass an equal and opposite force with energized coils. This is called **compass compensation**. When there is a possibility of confusion with compass adjustment to neutralize the effects of the natural magnetism of the vessel, the expression **degaussing compensation** is used. Since compensation may not be perfect, a small amount of deviation due to degaussing may remain on certain headings. This is the reason for swinging the ship with degaussing off and with it on. This procedure leads to having two separate columns in the deviation table.

641. A Vessel's Magnetic Signature

A simplified diagram of the distortion of the earth's magnetic field in the vicinity of a steel vessel is shown in Figure 641a. The field strength is directly proportional to the line spacing density. If a vessel passes over a device for detecting and recording the strength of the magnetic field, a certain pattern is traced. Figure 641b shows this pattern. Since the magnetic field of each vessel is different, each produces a distinctive trace. This distinctive trace is referred to as the vessel's **magnetic signature**.

Several **degaussing stations** have been established to determine magnetic signatures and recommend the currents needed in the various degaussing coils. Since a vessel's induced magnetism varies with heading and magnetic latitude, the current settings of the coils may sometimes need to be changed. A **degaussing folder** is provided each vessel to indicate the changes and to give other pertinent information.

A vessel's permanent magnetism changes somewhat with time and the magnetic history of the vessel. Therefore, the data in the degaussing folder should be checked periodically at the magnetic station.

642. Degaussing Coils

For degaussing purposes, the total field of the vessel is divided into three components: (1) vertical, (2) horizontal fore-and-aft, and (3) horizontal athwartships. The positive (+) directions are considered downward, forward, and to port, respectively. These are the normal directions for a vessel headed north or east in north latitude. Each

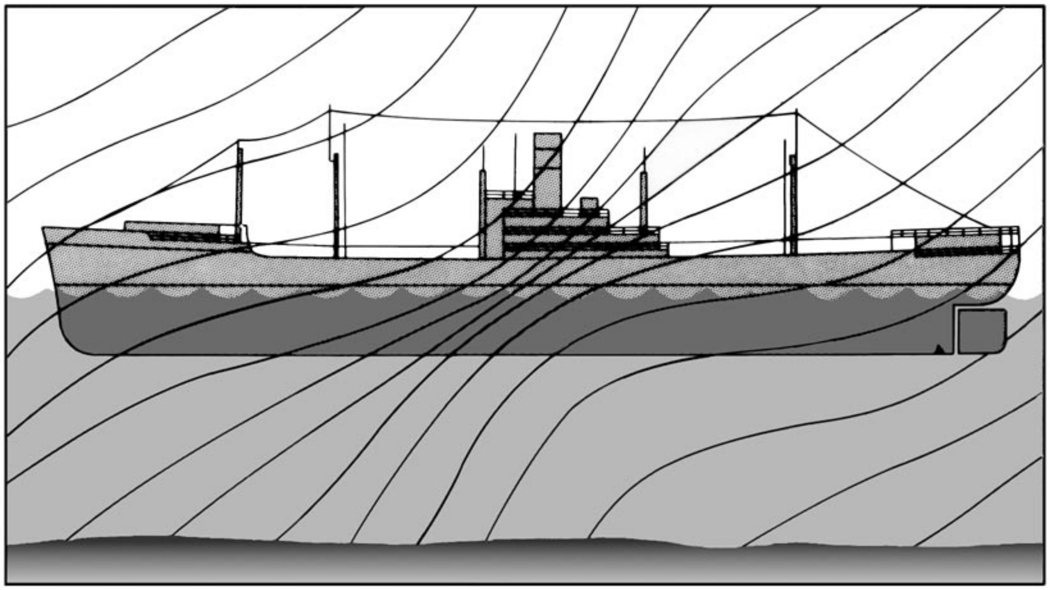


Figure 641a. Simplified diagram of distortion of earth's magnetic field in the vicinity of a steel vessel.

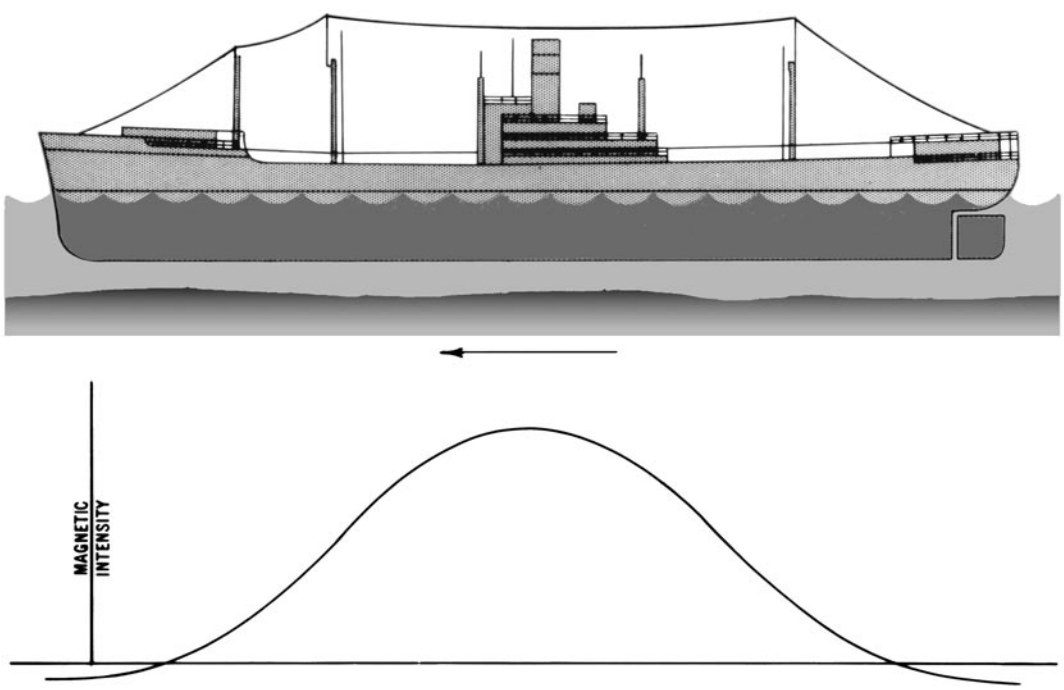


Figure 641b. A simplified signature of a vessel of Figure 641a.

component is opposed by a separate degaussing field just strong enough to neutralize it. Ideally, when this has been done, the earth's field passes through the vessel smoothly and without distortion. The opposing degaussing fields are produced by direct current flowing in coils of wire. Each of the degaussing coils is placed so that the field it produces is directed to oppose one component of the ship's field.

The number of coils installed depends upon the magnetic characteristics of the vessel, and the degree of safety desired. The ship's permanent and induced magnetism may be neutralized separately so that control of induced magnetism can be varied as heading and latitude change, without disturbing the fields opposing the vessel's permanent field. The principal coils employed are the following:

Main (M) coil. The M coil is horizontal and completely encircles the vessel, usually at or near the waterline. Its function is to oppose the vertical component of the vessel's permanent and induced fields combined. Generally the induced field predominates. Current in the M-coil is varied or reversed according to the change of the induced component of the vertical field with latitude.

Forecastle (F) and **quarterdeck (Q) coils**. The F and Q coils are placed horizontal just below the forward and after thirds (or quarters), respectively, of the weather deck. The designation "Q" for quarterdeck is reminiscent of the days before World War II when the "quarterdeck" of naval vessels was aft along the ship's quarter. These coils, in which current can be individually adjusted, remove much of the fore-and-aft component of the ship's permanent and induced fields. More commonly, the combined F and Q coils consist of two parts; one part the FP and QP coils, to take care of the permanent fore-and-aft field, and the other part, the FI and QI coils, to neutralize the induced fore-and-aft field. Generally, the forward and after coils of each type are connected in series, forming a split-coil installation and designated FP-QP coils and FI-QI coils. Current in the FP-QP coils is generally constant, but in the FI-QI coils is varied according to the heading and magnetic latitude of the vessel. In split-coil installations, the coil designations are often called simply the P-coil and I-coil.

Longitudinal (L) coil. Better control of the fore-and-aft components, but at greater installation expense, is provided by placing a series of vertical, athwartship coils along the length of the ship. It is the field, not the coils, which is longitudinal. Current in an L coil is varied as with the FI-QI coils. It is maximum on north and south headings, and zero on east and west headings.

Athwartship (A) coil. The A coil is in a vertical fore-and-aft plane, thus producing a horizontal athwartship field which neutralizes the athwartship component of the vessel's field. In most vessels, this component of the permanent field is small and can be ignored. Since the A-coil neutralizes the induced field, primarily, the current is changed with magnetic latitude and with heading, maximum on east or west headings, and zero on north or south headings.

The strength and direction of the current in each coil is indicated and adjusted at a control panel accessible to the navigator. Current may be controlled directly by rheostats at the control panel or remotely by push buttons which operate rheostats in the engine room.

Appropriate values of the current in each coil are determined at a degaussing station, where the various currents are adjusted until the vessel's magnetic signature is made as flat as possible. Recommended current values and directions for all headings and magnetic latitudes are set forth in the vessel's degaussing folder. This document is normally kept by the navigator, whose must see that the recommended settings are maintained whenever the degaussing system is energized.

643. Securing The Degaussing System

Unless the degaussing system is properly secured, residual magnetism may remain in the vessel. During degaussing compensation and at other times, as recommended in the degaussing folder, the "reversal" method is used. The steps in the reversal process are as follows:

1. Start with maximum degaussing current used since the system was last energized.
2. Decrease current to zero and increase it in the opposite direction to the same value as in step 1.
3. Decrease the current to zero and increase it to three-fourths maximum value in the original direction.
4. Decrease the current to zero and increase it to one-half maximum value in the opposite direction.
5. Decrease the current to zero and increase it to one-fourth maximum value in the original direction.
6. Decrease the current to zero and increase it to one-eighth maximum value in the opposite direction.
7. Decrease the current to zero and open switch.

644. Magnetic Treatment Of Vessels

In some instances, degaussing can be made more effective by changing the magnetic characteristics of the vessel by a process known as **deperming**. Heavy cables are wound around the vessel in an athwartship direction, forming vertical loops around the longitudinal axis of the vessel. The loops are run beneath the keel, up the sides, and over the top of the weather deck at closely spaced equal intervals along the entire length of the vessel. Predetermined values of direct current are then passed through the coils. When the desired magnetic characteristics have been acquired, the cables are removed.

A vessel which does not have degaussing coils, or which has a degaussing system which is inoperative, can be given some temporary protection by a process known as **flashing**. A horizontal coil is placed around the outside of the vessel and energized with large predetermined values of direct current. When the vessel has acquired a vertical field of permanent magnetism of the correct magnitude and polarity to reduce to a minimum the resultant field below the vessel for the particular magnetic latitude involved, the cable is removed. This type protection is not as satisfactory as

that provided by degaussing coils because it is not adjustable for various headings and magnetic latitudes, and also because the vessel's magnetism slowly readjusts following treatment.

During magnetic treatment all magnetic compasses and Flinders bars should be removed from the ship. Permanent adjusting magnets and quadrantal correctors are not materially affected, and need not be removed. If it is impractical to remove a compass, the cables used for magnetic treatment should be kept as far as practical from it.

645. Degaussing Effects

The degaussing of ships for protection against magnetic mines creates additional effects upon magnetic compasses, which are somewhat different from the permanent and induced magnetic effects. The degaussing effects are electromagnetic, and depend on:

1. Number and type of degaussing coils installed.
2. Magnetic strength and polarity of the degaussing coils.
3. Relative location of the different degaussing coils with respect to the binnacle.
4. Presence of masses of steel, which would tend to concentrate or distort magnetic fields in the vicinity of the binnacle.
5. The fact that degaussing coils are operated intermittently, with variable current values, and with different polarities, as dictated by necessary degaussing conditions.

646. Degaussing Compensation

The magnetic fields created by the degaussing coils would render the vessel's magnetic compasses useless unless compensated. This is accomplished by subjecting the compass to compensating fields along three mutually perpendicular axes. These fields are provided by small **compensating coils** adjacent to the compass. In nearly all installations, one of these coils, the **heeling coil**, is horizontal and on the same plane as the compass card, providing a vertical compensating field. Current in the heeling coil is adjusted until the vertical component of the total degaussing field is neutralized. The other compensating coils provide horizontal fields perpendicular to each other. Current is varied in these coils until their resultant field is equal and opposite to the horizontal component of the degaussing field. In early installations, these horizontal fields were directed fore-and-aft and athwartships by placing the coils around the Flinders bar and the quadrantal spheres. Compactness and other advantages are gained by placing the coils on perpendicular axes extending 045°-225° and 315°-135° relative to the heading. A frequently used compensating installation, called the **type K**, is shown in Figure 646. It consists of a heeling coil extending completely around the top of the binnacle, four **intercardinal coils**, and three control boxes. The intercardinal coils are named for their positions relative to the compass when the vessel is on a heading of north, and also for the compass headings on which the current in the coils is adjusted to the correct amount for compensation. The NE-SW coils operate together as one set, and the NW-SE coils operate as another. One control box is provided for each set, and one for the heeling coil.

The compass compensating coils are connected to the power supply of the degaussing coils, and the currents passing through the compensating coils are adjusted by series resistances so that the compensating field is equal to the degaussing field. Thus, a change in the degaussing currents is accompanied by a proportional change in the compensating currents. Each coil has a separate winding for each degaussing circuit it compensates.

Degaussing compensation is carried out while the vessel is moored at the shipyard where the degaussing coils are installed. This is usually done by civilian professionals, using the following procedure:

Step 1. The compass is removed from its binnacle and a dip needle is installed in its place. The M coil and heeling coil are then energized, and the current in the heeling coil is adjusted until the dip needle indicates the correct value for

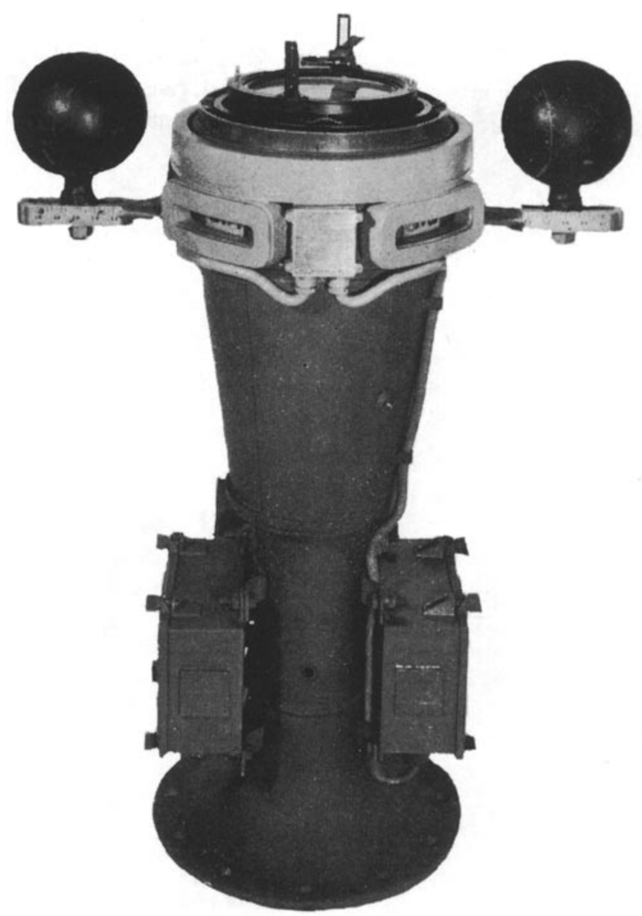


Figure 646. Type K degaussing compensation installation.

the magnetic latitude of the vessel. The system is then secured by the reversing process.

Step 2. The compass is replaced in the binnacle. With auxiliary magnets, the compass card is deflected until the compass magnets are parallel to one of the compensating coils or set of coils used to produce a horizontal field. The compass magnets are then *perpendicular* to the field produced by that coil. One of the degaussing circuits producing a horizontal field, and its compensating winding, are then energized, and the current in the compensating winding is adjusted until the compass reading returns to the value it had before the degaussing circuit was energized. The system is then secured by the reversing process. The process is repeated with each additional circuit used to create a horizontal field. The auxiliary magnets are then removed.

Step 3. The auxiliary magnets are placed so that the compass magnets are parallel to the other compensating coils or set of coils used to produce a horizontal field. The procedure of step 2 is then repeated for each circuit producing a horizontal field.

When the vessel gets under way, it proceeds to a suitable maneuvering area. The vessel is then headed so that the compass magnets are parallel first to one compensating coil or set of coils and then the other, and any needed adjustment is made in the compensating circuits to reduce the error to a minimum. The vessel is then swung for residual deviation, first with degaussing off and then with degaussing on, and the correct current settings for each heading at the magnetic latitude of the vessel. From the values thus obtained, the “DG OFF” and “DG ON” columns of the deviation table are filled in. If the results indicate satisfactory compensation, a record is made of the degaussing coil settings and the resistance, voltages, and currents in the compensating coil circuits. The control boxes are then secured.

Under normal operating conditions, the settings need not be changed unless changes are made in the degaussing system, or unless an alteration is made in the amount of Flinders bar or the setting of the quadrantal correctors. However, it is possible for a ground to occur in the coils or control box if the circuits are not adequately protected from moisture. If this occurs, it should be reflected by a change in deviation with degaussing on, or by a decreased installation resistance. Under these conditions, compensation should be done again. If the compass will be used with degaussing on before the ship can be returned to a shipyard where the compensation can be made by experienced personnel, the compensation should be made at sea on the actual headings needed, rather than by deflection of the compass needles by magnets. More complete information related to this process is given in the degaussing folder.

If a vessel has been given magnetic treatment, its magnetic properties have been changed. This necessitates readjustment of *each* magnetic compass. This is best delayed for several days to permit stabilization of the magnetic characteristics of the vessel. If compensation cannot be delayed, the vessel should be swung again for residual deviation after a few days. Degaussing compensation should not be made until after compass adjustment has been completed.

CHAPTER 7

DEAD RECKONING

DEFINITION AND PURPOSE

700. The Importance Of Dead Reckoning

Dead reckoning allows a navigator to determine his present position by projecting his past courses steered and speeds over ground from a known past position. He can also determine his future position by projecting an ordered course and speed of advance from a known present position. The DR position is only an approximate position because it does not allow for the effect of leeway, current, helmsman error, or gyro error.

Dead reckoning helps in determining sunrise and sunset; in predicting landfall, sighting lights and predicting arrival times; and in evaluating the accuracy of electronic positioning information. It also helps in predicting which celestial bodies will be available for future observation.

The navigator should carefully tend his DR plot, update it when required, use it to evaluate external forces acting on his ship, and consult it to avoid potential navigation hazards.

CONSTRUCTING THE DEAD RECKONING PLOT

Maintain the DR plot directly on the chart in use. DR at least two fix intervals ahead while piloting. If transiting in the open ocean, maintain the DR at least four hours ahead of the last fix position. If operating in a defined, small operating area, there is no need to extend the DR out of the operating area; extend it only to the operating area boundary. Maintaining the DR plot directly on the chart allows the navigator to evaluate a vessel's future position in relation to charted navigation hazards. It also allows the conning officer and captain to plan course and speed changes required to meet any operational commitments.

This section will discuss how to construct the DR plot.

701. Measuring Courses And Distances

To measure courses, use the chart's compass rose nearest to the chart section currently in use. Transfer course lines to and from the compass rose using parallel rulers, rolling rulers, or triangles. If using a parallel motion plotter (PMP), simply set the plotter at the desired course and plot that course directly on the chart.

The navigator can measure direction at any convenient place on a Mercator chart because the meridians are parallel to each other and a line making an angle with any one makes the same angle with all others. Measure direction on a conformal chart having nonparallel meridians at the meridian closest to the area of the chart in use. The only common nonconformal projection used is the gnomonic; a gnomonic chart usually contains instructions for measuring direction.

Compass roses give both true and magnetic directions. For most purposes, use true directions.

Measure distances using the chart's latitude scale. Assuming that one minute of latitude equals one nautical mile introduces no significant error. Since the Mercator's latitude scale expands as latitude increases, measure distances on the latitude scale closest to the area of interest. On large scale charts, such as harbor charts, use the distance scale provided. To measure long distances on small-scale charts, break the distance into a number of segments and measure each segment at its mid-latitude.

Navigational computers can also compute distances between two points. Because of the errors inherent in manually measuring track distances, use a navigation computer if one is available.

702. Plotting And Labeling The Course Line And Positions

Draw a new **course line** whenever restarting the DR. Extend the course line from a fix in the direction of the ordered course. Above the course line place a capital C followed by the ordered course. Below the course line, place a capital S followed by the speed in knots. Label all course lines and fixes soon after plotting them because a conning officer or navigator can easily misinterpret an unlabeled line or position.

Enclose a fix from two or more LOPs by a small circle and label it with the time to the nearest minute. Mark a DR position with a semicircle and the time. Mark an **estimated position (EP)** by a small square and the time. Determining an EP is covered later in this chapter.

Express the time using four digits without punctuation. Use either zone time or GMT.

Label the plot neatly, succinctly, and clearly.

Figure 702 illustrates this process. The navigator plots and labels the 0800 fix. The conning officer orders a course

of 095°T and a speed of 15 knots. The navigator extends the course line from the 0800 fix in a direction of 095°T. He calculates that in one hour at 15 knots he will travel 15 nautical miles. He measures 15 nautical miles from the 0800 fix position along the course line and marks that point on the course line with a semicircle. He labels this DR with the time. Note that, by convention, he labels the fix time horizontally and the DR time diagonally.

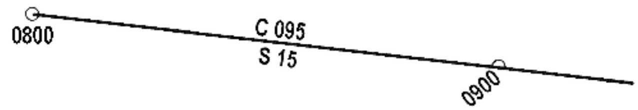


Figure 702. A course line with labels.

THE RULES OF DEAD RECKONING

703. Plotting The DR

Plot the vessel's DR position:

1. At least every hour on the hour.
2. After every change of course or speed.
3. After every fix or running fix.
4. After plotting a single line of position.

Figure 703 illustrates applying these rules. Clearing the harbor at 0900, the navigator obtains a last visual fix. This is **taking departure**, and the position determined is called the **departure**. At the 0900 departure, the conning officer orders a course of 090°T and a speed of 10 knots. The navigator lays out the 090°T course line from the departure.

At 1000, the navigator plots a DR position according to the rule requiring plotting a DR position at least every hour on the hour. At 1030, the conning officer orders a course change to 060°T. The navigator plots the 1030 DR position in accordance with the rule requiring plotting a DR position at every course and speed change. Note that the course line changes at 1030 to 060°T to conform to the new course. At 1100, the conning officer changes course back to 090°T. The navigator plots an 1100 DR because of the course change, Note that, regardless of the course change, an 1100 DR would have been required because of the "every hour on the hour" rule.

At 1200, the conning officer changes course to 180°T and speed to 5 knots. The navigator plots the 1200 DR. At 1300, the navigator obtains a fix. Note that the fix position is offset to the east from the DR position. The navigator determines set and drift from this offset and applies this set and drift to any DR position from 1300 until the next fix to determine an estimated position. He also resets the DR to the fix; that is, he draws the 180°T course line from the 1300 fix, not the 1300 DR.

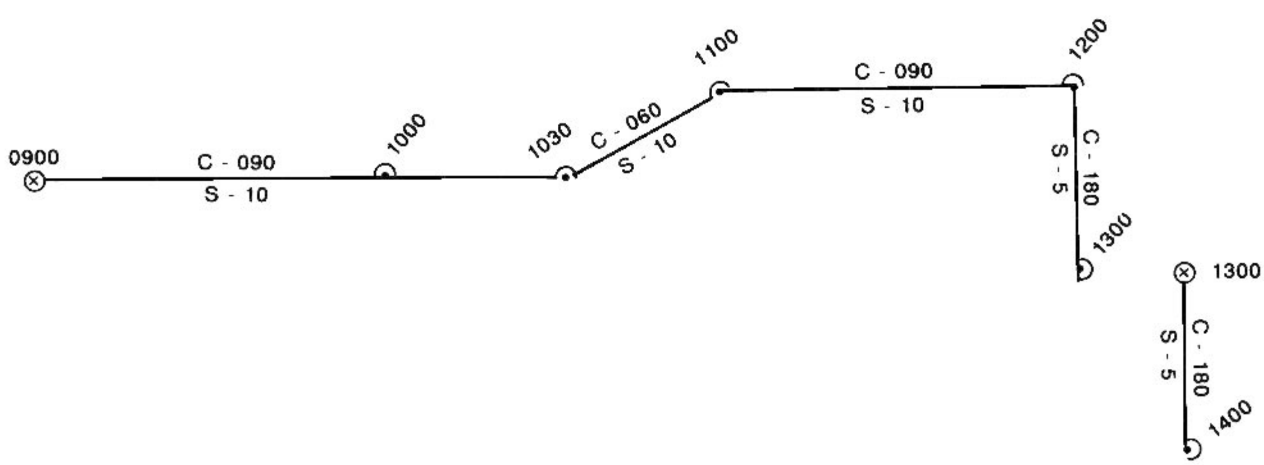


Figure 703. A typical dead reckoning plot.

704. Resetting The DR

Reset the DR plot to the ship's latest fix or running fix. In addition, consider resetting the DR to an inertial estimated position as discussed below.

If a navigator has not received a fix for a long time, the DR plot, not having been reset to a fix, will accumulate time-dependent error. Soon that error may become so significant that the DR will no longer show the ship's position with sufficient accuracy. If his vessel is equipped with an inertial navigator, the navigator should consider resetting the DR to the inertial estimated position. Some factors to consider when making this determination are:

(1) Time since the last fix and availability of fix information. If it has been a short time since the last fix and fix information may soon become available, it may be advisable to wait for the next fix to reset the DR.

(2) Dynamics of the navigation situation. If, for example, a submerged submarine is operating in the Gulf Stream, fix information is available but operational considerations may preclude the submarine from going to periscope depth to obtain a fix. Similarly, a surface ship with an inertial navigator may be in a dynamic current and suffer a temporary loss of electronic fix equipment. In either case, the fix information will be available shortly but the dynamics of the situation call for a more accurate assessment of the vessel's position. Plotting an inertial EP and resetting the DR to that EP may provide the navigator with a more accurate assessment of the navigation situation.

(3) Reliability and accuracy of the fix source. If a submarine is operating under the ice, for example, only the inertial EP and Omega fixes may be available for weeks at a time. Given a known inaccuracy of Omega, a high prior correlation between the inertial EP and highly accurate fix systems such as GPS, and the continued proper operation of the inertial navigator, the navigator may well decide to reset the DR to the inertial EP rather than the Omega fix.

DEAD RECKONING AND SHIP SAFETY

Properly maintaining a DR plot is important for ship safety. The DR allows the navigator to examine a future position in relation to a planned track. It allows him to anticipate charted hazards and plan appropriate action to avoid them. Recall that the DR position is only approximate. Using a concept called **fix expansion** compensates for the DR's inaccuracy and allows the navigator to use the DR more effectively to anticipate and avoid danger.

705. Fix Expansion

Often a ship steams in the open ocean for extended periods without a fix. This can result from of any number of factors ranging from the inability to obtain celestial fixes to malfunctioning electronic navigation systems. Infrequent fixes are particularly common on submarines. Whatever the reason, in some instances a navigator may find himself in the position of having to steam many hours on DR alone.

The navigator must take precautions to ensure that all hazards to navigation along his path are accounted for by the approximate nature of a DR position. One method which can be used is **fix expansion**.

Fix expansion takes into account possible errors in the DR calculation caused by factors which tend to affect the vessel's actual course and speed over ground. The navigator considers all such factors and develops an expanding "error circle" around the DR plot. One of the basic assumptions of fix expansion is that the various individual effects of current, leeway, and steering error combine to cause a cumulative error which increases over time, hence, the concept of *expansion*.

Errors considered in the calculation of the fix expansion encompass all errors that can lead to DR inaccuracy. Some of the most important factors are current and wind, compass or gyro error, and steering error. Any method which attempts to determine an error circle must take these factors into account. The navigator can use the magnitude of set and drift calculated from his DR plot. See section 707 below. He can obtain the current's magnitude from pilot charts or weather reports. He can determine wind speed from weather reports or direct measurement. He can determine compass error by comparison with an accurate standard or by obtaining an azimuth of the sun. The navigator determines the effect each of these errors has on his course and speed over ground, and applies that error to the fix expansion calculation.

As noted above, the error is a function of time; it grows as the ship proceeds down the track without a obtaining a fix. Therefore, the navigator must incorporate his calculated errors into an **error circle** whose radius grows with time. For example, assume the navigator calculates that all the various sources of error can create a cumulative position error of no more than 2 nm. Then his fix expansion error circle would grow at that rate; it would be 2 nm after the first hour, 4 nm after the second, and so on.

At what value should the navigator start this error circle? Recall that a DR is laid out from every fix. All fix sources have a finite absolute accuracy, and the initial error circle should reflect that accuracy. Assume, for example, that a satellite navigation system has an accuracy of 0.5 nm. Then the initial error circle around that fix should be set at 0.5 nm.

Construct the error circle as follows. When the navigator obtains a fix, reset the DR to that fix. Then, enclose that DR position in a circle the radius of which is equal to the accuracy of the system used to obtain the fix. Lay out the ordered

course and speed from the fix position. Then, apply the fix expansion circle to the hourly DR's. In the example given above, the DR after one hour would be enclosed by a circle of radius 2.5 nm, after two hours 4.5 nm, and so on. Having encircled the four hour DR positions with the error circles, the navigator then draws two lines originating tangent to the original error circle and simultaneously tangent to the other error circles. The navigator then closely examines the area between the two tangent lines for hazards to navigation. This technique is illustrated in Figure 705 below.

The fix expansion encompasses *all the area in which the vessel could be located* (as long as all sources of error are considered). If any hazards are indicated within the cone, the navigator should be especially alert for those dangers. If, for example, the fix expansion indicates that the vessel may be standing into shoal water, continuously monitor the fathometer. Similarly, if the fix expansion indicated that the vessel might be approaching a charted obstruction, post extra lookouts.

The fix expansion may grow at such a rate that it becomes unwieldy. Obviously, if the fix expansion grows to cover too large an area, it has lost its usefulness as a tool for the navigator, and he should obtain a new fix.

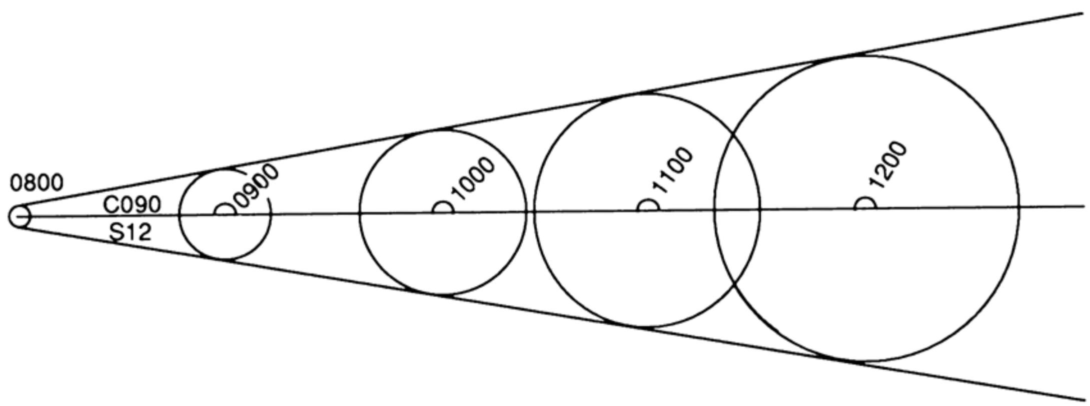


Figure 705. Fix expansion. All possible positions of the ship lie between the lines tangent to the expanding circles. Examine this area for dangers.

DETERMINING AN ESTIMATED POSITION

An estimated position is a DR position corrected for the effects of leeway, steering error, and current. This section will briefly discuss the factors that cause the DR position to diverge from the vessel's actual position. It will then discuss calculating set and drift and applying these values to the DR to obtain an estimated position. Finally, it will discuss determining the estimated course and speed made good.

706. Factors Affecting DR Position Accuracy

Tidal current is the periodic horizontal movement of the water's surface caused by the tide-affecting gravitational force of the moon. **Current** is the horizontal movement of the sea surface caused by meteorological, oceanographic, or topographical effects. From whatever its source, the horizontal motion of the sea's surface is an important dynamic force acting on a vessel moving through the water. **Set** refers to the current's direction, and **drift** refers to the current's speed.

Leeway is the leeward motion of a vessel due to that component of the wind vector perpendicular to the vessel's track.

Leeway and current effects combine to produce the most pronounced natural dynamic effects on a transiting vessel.

In addition to these natural forces, helmsman error and gyro error combine to produce a **steering error** that causes additional error in the DR.

707. Calculating Set And Drift And Plotting An Estimated Position

It is difficult to quantify the errors discussed above individually. However, the navigator can easily quantify their cumulative effect by comparing simultaneous fix and DR positions. Were there no dynamic forces acting on the vessel and no steering error, the DR position and the fix position would coincide. However, they seldom coincide. The fix is offset from the DR by a finite distance. This offset is caused by the error factors discussed above.

Note again that this methodology provides no means to determine the magnitude of the individual errors. It simply provides the navigator with a measurable representation of their combined effect.

When the navigator measures this combined effect, he often refers to it as the "set and drift." Recall from above that these terms technically were restricted to describing current effects. However, even though the fix-to-DR offset is caused by effects in addition to the current, this text will follow the convention of referring to the offset as the set and drift.

The set is the direction from the DR to the fix. The drift is the distance in miles between the DR and the fix divided by the number of hours since the DR was last reset. This is true regardless of the number of changes of course or speed since the last fix. Calculate set and drift at every fix.

Calculate an EP by drawing from a DR position a vector whose direction equals the set and whose magnitude equals the product of the drift and the number of hours since the last DR reset. See Figure 707. From the 0900 DR position the navigator draws a set and drift vector. The end of that vector marks the 0900 EP. Note that the EP is enclosed in a square and labeled horizontally with the time. Plot and evaluate an EP with every DR position.

708. Estimated Course And Speed Made Good

The direction of a straight line from the last fix to the EP is the **estimated track made good**. The length of this line divided by the time between the fix and the EP is the **estimated speed made good**.

Solve for the estimated track and speed by using a vector diagram. See the example problems below. See. Figure 708a

Example 1: *A ship on course 080°, speed 10 knots, is steaming through a current having an estimated set of 140° and drift of 2 knots.*

Required: *Estimated track and speed made good.*

Solution: *See Figure 708a. From A, any convenient point, draw AB, the course and speed of the ship, in direction 080°, for a distance of 10 miles.*

From B draw BC, the set and drift of the current, in direction 140°, for a distance of 2 miles.

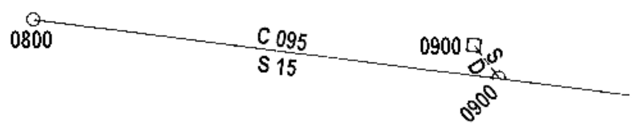


Figure 707. Determining an estimated position.

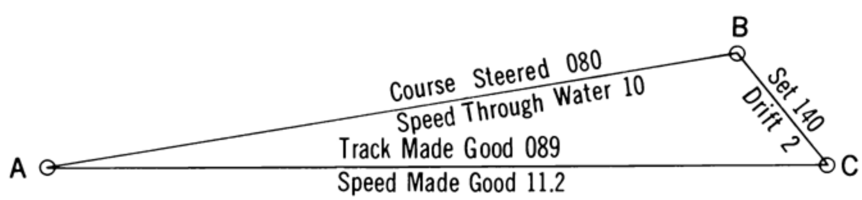


Figure 708a. Finding track and speed made good through a current.

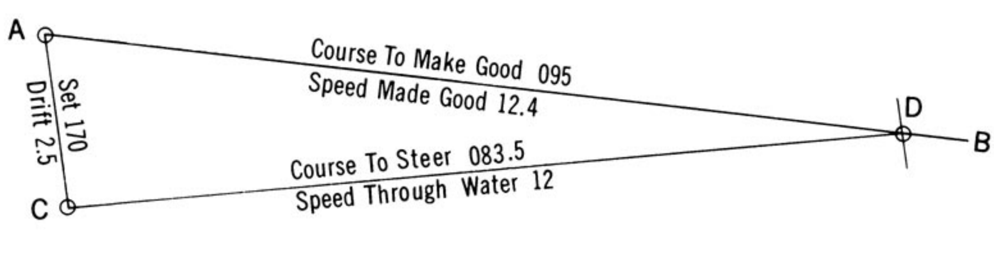


Figure 708b. Finding the course to steer at a given speed to make good a given course through a current.

The direction and length of AC are the estimated track and speed made good.

Answers: *Estimated track made good 089°, estimated speed made good 11.2 knots.*

To find the course to steer at a given speed to make good a desired course, plot the current vector from the origin, A, instead of from B. See Figure 708b.

Example 2: *The captain desires to make good a course of 095° through a current having a set of 170° and a drift of 2.5 knots, using a speed of 12 knots.*

Required: *The course to steer and the speed made good.*

Solution: *See Figure 708b. From A, any convenient point, draw line AB extending in the direction of the course to be made good, 095°.*

From A draw AC, the set and drift of the current.

Using C as a center, swing an arc of radius CD, the speed through the water (12 knots), intersecting line AB at D.

Measure the direction of line CD, 083.5°. This is the course to steer.

Measure the length AD, 12.4 knots. This is the speed made good.

Answers: *Course to steer 083.5°, speed made good 12.4 knots.*

To find the course to steer and the speed to use to make good a desired course and speed, proceed as follows: See Figure 708c.

Example 3: *The captain desires to make good a course of 265° and a speed of 15 knots through a current having a set of 185° and a drift of 3 knots.*

Required: *The course to steer and the speed to use.*

Solution: *See Figure 708c. From A, any convenient point, draw AB in the direction of the course to be made good, 265° and for length equal to the speed to be made good, 15 knots.*

From A draw AC, the set and drift of the current.

Draw a straight line from C to B. The direction of this line, 276°, is the required course to steer; and the length, 14.8 knots, is the required speed.

Answers: *Course to steer 276°, speed to use 14.8 kn.*

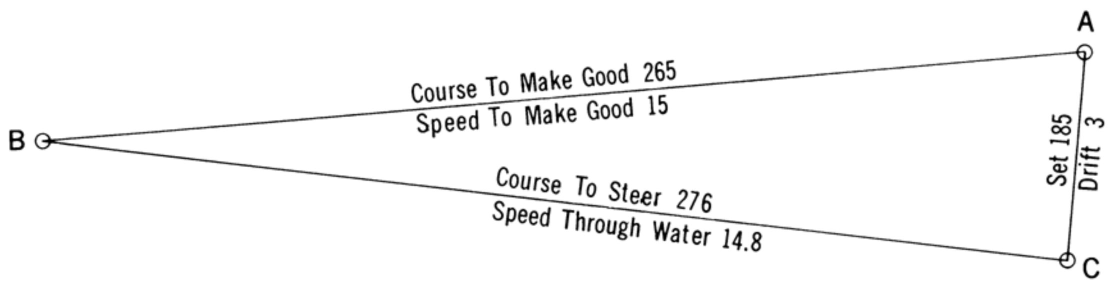


Figure 708c. Finding course to steer and speed to use to make good a given course and speed through the current.

CHAPTER 8

PILOTING

DEFINITION AND PURPOSE

800. Introduction

Piloting involves navigating a vessel through restricted waters. As in all other phases of navigation, proper preparation and strict attention to detail are very important. This chapter will discuss a piloting methodology designed to ensure the procedure is carried out safely and efficiently. These procedures will vary from vessel to vessel according to the skill and composition of the piloting team. It is the responsibility of the navigator to choose the procedures applicable to his own situation.

PREPARATION

801. Chart Preparation

- **Assemble Required Publications:** These publications should include *Coast Pilots, Sailing Directions, Light Lists, Lists of Lights, Tide Tables, Tidal Current Tables, Notice to Mariners*, and *Local Notice to Mariners*. Often, for military vessels, a port will be under the operational direction of a particular squadron; obtain that squadron's port Operation Order. Civilian vessels should obtain the port's harbor regulations. These publications will cover local regulations such as speed limits and bridge-to-bridge radio frequency monitoring requirements. Assemble the broadcast Notice to Mariners file.

- **Select and Correct Charts:** Choose the largest scale chart available for the approach. Often, the harbor approach will be too long to be represented on only one chart. For example, three charts are required to cover the waters from the Naval Station in Norfolk to the entrance of the Chesapeake Bay. Therefore, obtain all the charts required to cover the entire passage. Verify using the Notice to Mariners that the charts in use have been corrected through the latest change. Make any required changes prior to using the chart. Check the *Local Notice to Mariners* and the *Broadcast Notice to Mariners* file to ensure the chart is fully corrected and up to date. Annotate on the chart or a chart correction card all the corrections that have been made; this will make it easier to verify the chart's correction status prior to its next use. Naval ships will normally prepare three sets of charts. One set is for the primary plot, the second set is for the secondary plot, and the third set is for the conning officer and captain.

- **Mark the Minimum Depth Contour:** Determine the minimum depth of water in which the vessel can safely operate and outline that depth contour on the chart. Do this step before doing any other harbor piloting planning. Make this outline in a bright color so that it clearly stands out. Carefully examine the area inside the contour and mark the isolated shoals less than the minimum depth which fall inside the marked contour. Determine the minimum depth in which the vessel can operate as follows:

  Minimum Depth = Ship's Draft – Height of Tide + Safety Margin + Squat. (See section 802 and section 819.)

Remember that often the fathometer's transducer is not located at the section of the hull that extends the furthest below the waterline. Therefore, the indicated depth of water below the fathometer transducer, not the depth of water below the vessel's deepest draft.

- **Highlight Selected Visual Navigation Aids (NAVAIDS):** Circle, highlight, and label all NAVAIDS on the chart. Consult the applicable *Coast Pilot* or *Sailing Directions* to determine a port's best NAVAIDS if the piloting team has not visited the port previously. These aids can be lighthouses, piers, shore features, or tanks; any prominent feature that is displayed on the chart can be used as a NAVAID. Label critical buoys, such as those marking a harbor entrance or a traffic separation scheme. Verify charted lights against the *Light List* or the *List of Lights* to confirm the charted information is correct. This becomes most critical when attempting to identify a light at night. Label NAVAIDS succinctly and clearly. Ensure everyone in the navigation team re-

fers to a NAVAID using the same terminology. This will reduce confusion between the bearing taker, the bearing recorder, and plotter.

- **Highlight Selected Radar NAVAIDS:** Highlight radar NAVAIDS with a triangle instead of a circle. If the NAVAID is suitable for either visual or radar piloting, it can be highlighted with either a circle or a triangle.

- **Plot the Departure/Approach Track:** This process is critical for ensuring safe pilotage. Consult the *Fleet Guide* and *Sailing Directions* for recommendations on the best track to use. Look for any information or regulations published by the local harbor authority. Lacking any of this information, locate a channel or safe route delineated on the chart and plot the vessel's track through the channel. Most U.S. ports have well-defined channels marked with buoys. Carefully check the intended track to ensure a sufficient depth of water under the keel will exist for the entire passage. If the scale of the chart permits, lay the track out to the starboard side of the channel to allow for any vessel traffic proceeding in the opposite direction. Many channels are marked by natural or man-made **ranges**. A range consists of two NAVAIDS in line with the center of a navigable channel. The navigator can determine his position relative to the track by evaluating the alignment of the NAVAIDS forming the range. These ranges should be measured to the nearest 0.1°, and this value should be marked on the chart. Not only are ranges useful in keeping a vessel on track, they are invaluable for determining gyro error. See section 808.

- **Label the Departure/Approach Track:** Label the track course to the nearest 0.5°. Similarly, label the distance of each track leg. Place these labels well off the track so they do not interfere with subsequent plotting. Highlight the track courses for easy reference while piloting. There is nothing more frustrating than approaching a turn and not being able to determine the next course from the chart quickly. Often a navigator might plan two separate tracks. One track would be for use during good visibility and the other for poor visibility. Considerations might include concern for the number of turns (fewer turns for poor visibility) or proximity to shoal water (smaller margin for error might be acceptable in good visibility). In this case, label both tracks as above and appropriately mark when to use each track. If two separate tracks are provided, the navigator must decide which one to use *before* the ship enters restricted waters. Never change tracks in the middle of the transit.

- **Use Advance and Transfer to Determine Turning Points:** The track determined above does not take into account **advance** and **transfer** for determining turning points. See Figure 801a. The distance the vessel moves in

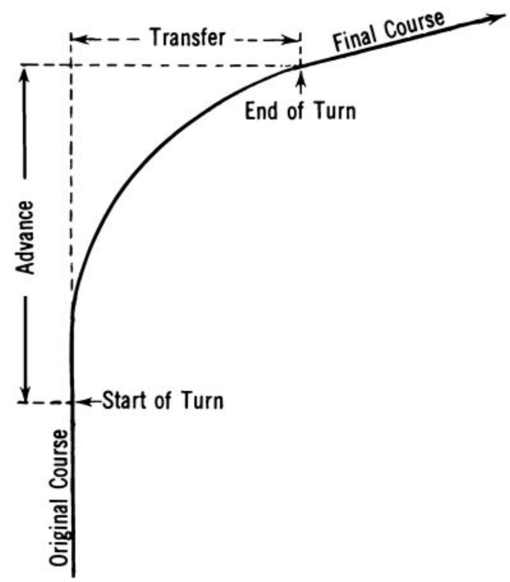


Figure 801a. Advance and transfer.

the direction of the original course from when the rudder is put over until the new course is reached is called advance. The distance the vessel moves perpendicular to the original course during the turn is called transfer. Use the advance and transfer characteristics of the vessel to determine when the vessel must put its rudder over to gain the next course. From that point, fair in a curve between the original course and the new course. Mark the point on the original course where the vessel must put its rudder over as the **turning point**. See Figure 801b.

- **Plot Turn Bearings:** A **turn bearing** is a predetermined bearing to a charted object from the track point at which the rudder must be put over in order to make a desired turn. Follow two rules when selecting NAVAIDS to be used as turn bearing sources: (1) The NAVAID should be as close to the beam as possible at the turn point; and (2) The aid should be on the inside elbow of the turn. This ensures the largest rate of bearing change at the turning point, thus marking the turning point more accurately. Plot the turn bearing to the selected NAVAID from the point on the track at which the vessel must put its rudder over to gain the new course. Label the bearing to the nearest 0.1°.

Example: *Figure 801b illustrates using advance and transfer to determine a turn bearing. A ship proceeding on course 100° is to turn 60° to the left to come on a range which will guide it up a channel. For a 60° turn and the amount of rudder used, the advance is 920 yards and the transfer is 350 yards.*

Required: *The bearing of flagpole "FP." when the rudder is put over.*

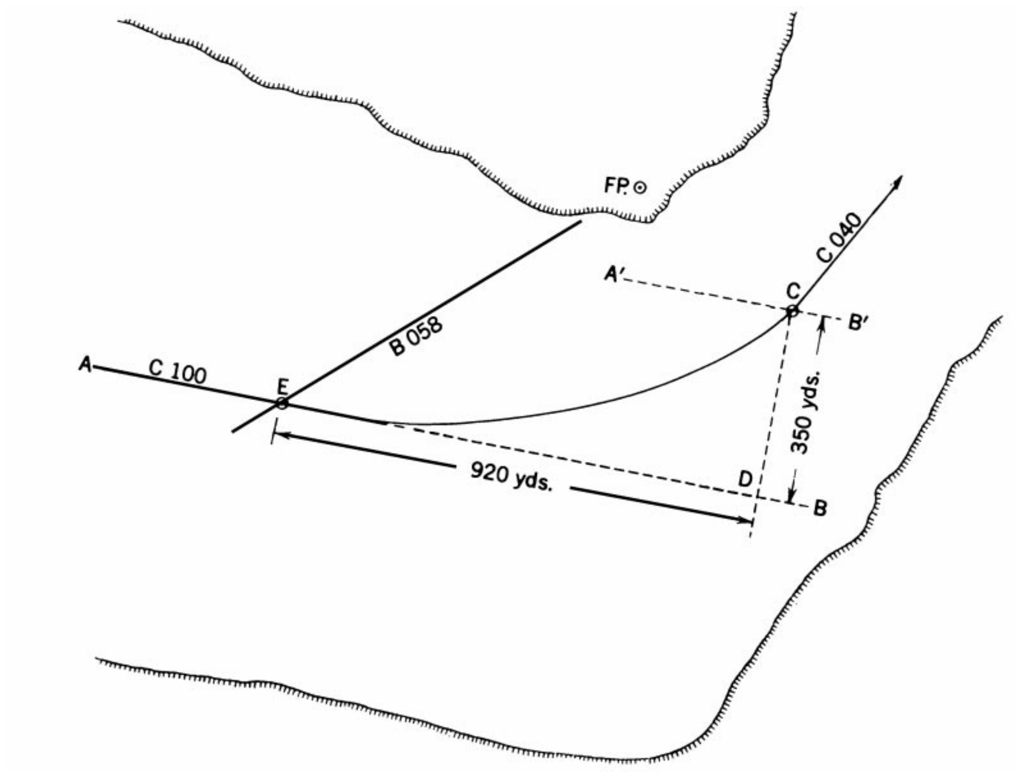


Figure 801b. Allowing for advance and transfer.

Solution:

1. *Extend the original course line, AB.*
2. *At a perpendicular distance of 350 yards, the transfer, draw a line A'B' parallel to the original course line AB. The point of intersection, C, of A'B' with the new course line is the place at which the turn is to be completed.*
3. *From C draw a perpendicular, CD, to the original course line, intersecting at D.*
4. *From D measure the advance, 920 yards, back along the original course line. This locates E, the point at which the turn should be started.*
5. *The direction of "FP." from E, 058°, is the bearing when the turn should be started.*

Answer: *Bearing 058°.*

- **Plot a Slide Bar for Every Turn Bearing:** To assist the navigator in quickly revising a turn bearing if the ship finds itself off track immediately prior to a turn, use a plotting technique known as the **slide bar**. See Figure 801c. Draw the slide bar parallel to the new course through the turning point on the original course. The navigator can quickly determine a new turn bearing by dead reckoning ahead from the vessel's last fix position to where the DR intersects the slide bar. The revised turn bearing is simply the bearing from that intersection point to the turn bearing NAVAID.

  Draw the slide bar with a different color from that used to lay down the track. The chart gets cluttered around a turn, and the navigator must be able to see the slide bar clearly.

- **Label Distance to Go From Each Turn Point:** At each turning point, label the distance to go until either the ship moors (inbound) or the ship clears the harbor (outbound). For an inbound transit, a vessel's captain is more concerned about *time* of arrival, so assume a speed of advance and label each turn point with time to go until mooring.

- **Plot Danger Bearings:** Danger bearings warn a navigator he may be approaching a navigation hazard too closely. See Figure 801d. Vector AB indicates a vessel's intended track. This track passes close to the indicated shoal. Draw a line from the NAVAID H tangent to the shoal. The bearing of that tangent line measured from the ship's track is 074.0°T. In other words, as long as NAVAID H bears *less than* 074°T as the vessel proceeds down its track, the vessel will not ground on the shoal. Hatch the side of the bearing line on the side of the hazard and label the danger bearing NMT (no more than) 074.0°T. For an added margin of safety, the line does not have to be drawn exactly tangent to the shoal. Perhaps, in this case, the navigator might want to set an error margin and draw the danger bearing at 065°T from NAVAID H. Lay down a danger bearing from any appropriate NAVAID in the

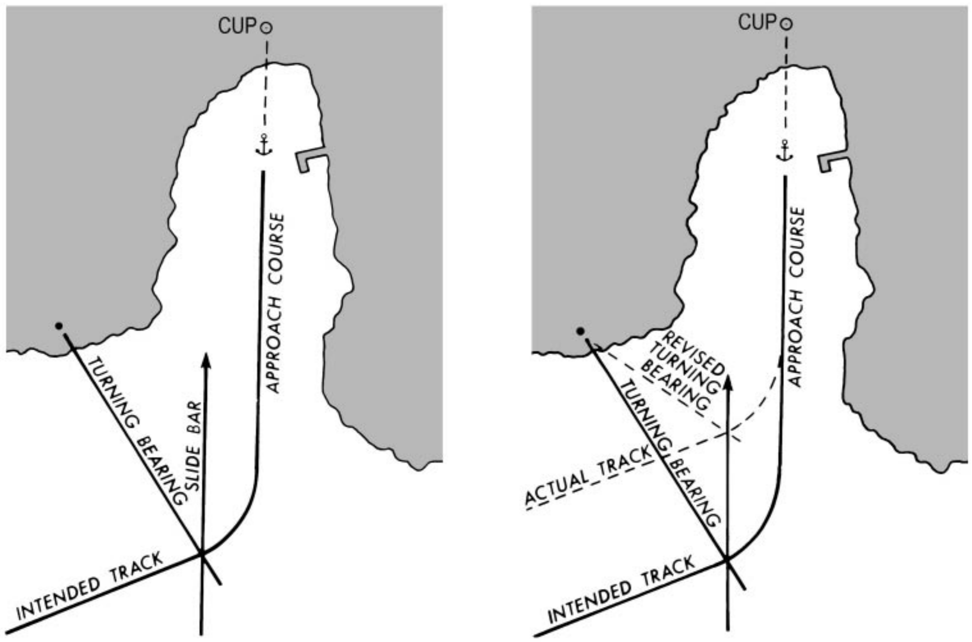


Figure 801c. The slide bar technique.

vicinity of any hazard to navigation. Ensure the track does not cross any danger bearing.

- **Plot Danger Ranges:** The danger range is analogous to the danger bearing. It is a standoff range from an object to prevent the vessel from approaching a hazard too closely.

- **Label Warning and Danger Soundings:** To determine the danger sounding, examine the vessel's proposed track and note the minimum expected sounding. The minimum expected sounding is the difference between the shallowest water expected on the transit and the vessel's maximum draft. Set 90% of this difference as the warning sounding and 80% of this difference as the danger sounding. This is not an inflexible rule. There may be peculiarities about the local conditions that will cause the navigator to choose another method of determining his warning and danger soundings. Use the above method if no other means is more suitable. For example: A vessel draws a maximum of 20 feet, and it is entering a channel dredged to a minimum depth of 50 feet. Set the warning and danger soundings at 0.9 (50ft. - 20ft) = 27ft and 0.8 (50ft. - 20ft.) = 24ft., respectively. Re-evaluate these soundings at different intervals along the track when the

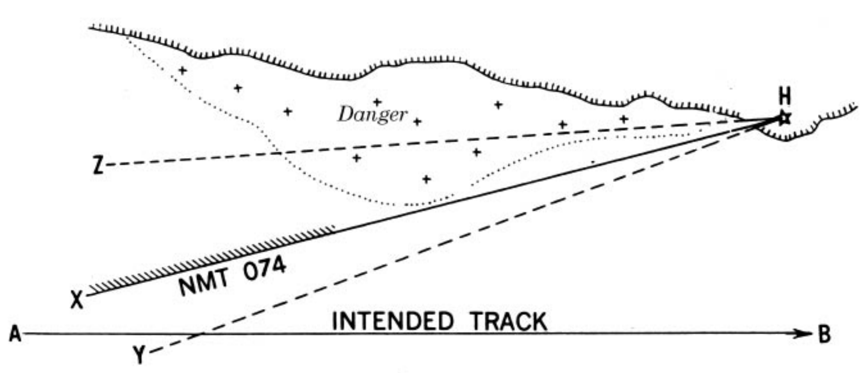


Figure 801d. A danger bearing, hatched on the dangerous side, labeled wih the appropriate bearing.

minimum expected sounding may change. Carefully label the points along the track between which these warning and danger soundings apply.

- **Label Demarcation Line:** Clearly label the point on the ship's track at which the Inland and International Rules of the Road apply. This is applicable only when piloting in U.S. ports.

- **Mark Speed Limits Where Applicable:** Often a harbor will have a local speed limit in the vicinity of piers, other vessels, or shore facilities. Mark these speed limits and the points between which they are applicable on the chart.

- **Mark the Point of Pilot Embarkation:** Some ports require vessels over a certain size to embark a pilot. If this is the case, mark the point on the chart where the pilot is to embark.

- **Mark the Tugboat Rendezvous Point:** If the vessel requires a tug to moor, mark the tug rendezvous point on the chart.

- **Mark the Chart Shift Point:** If more than one chart will be required to complete the passage, mark the track point where the navigator should shift to the next chart.

- **Harbor Communications:** Mark the point on the chart where the vessel must contact harbor control. Also mark the point where a vessel must contact its parent squadron to make an arrival report (military vessels only).

- **Tides and Currents:** Mark the points on the chart for which the tides and currents were calculated.

802. Tides And Currents

Determining the tidal and current conditions of the port which you are entering is crucial. Determining tides and currents is covered in Chapter 9. Plot a graph of the tidal range at the appropriate port for a 24-hour period for the day of your scheduled arrival or departure. Plotting the curve for the 24-hour period will cover those contingencies that delay your arrival or departure. Depending on a vessel's draft and the harbor's depth, some vessels may be able to transit only at high tide. If this is this case, it is critically important to determine the time and range of the tide correctly.

The magnitude and direction of the current will give the navigator some idea of the **set and drift** the vessel will experience during the transit. This will allow him to plan in advance for any potential current effects in the vicinity of navigation hazards.

803. Weather

The navigator should obtain a weather report covering the route which he intends to transit. This will allow him to prepare for any heavy weather by stationing extra lookouts, adjusting his speed for poor visibility, and preparing for radar navigation. If the weather is thick, he may want to consider standing off the harbor until it clears.

The navigator can receive weather information any number of ways. Military vessels receive weather reports from their parent squadrons prior to coming into port. Marine band radio carries continuous weather reports. Some vessels are equipped with weather facsimile machines. Some navigators carry cellular phones to reach shoreside personnel and harbor control; these can be used to get weather reports. However he obtains the information, the navigator should have a good idea of the weather where he will be piloting.

804. The Piloting Brief

Assemble the entire navigation team for a piloting brief prior to entering or leaving port. The vessel's captain and navigator should conduct the briefing. All navigation and bridge personnel should attend. The pilot, if he is already on board, should also attend. If the pilot is not onboard when the ship's company is briefed, the navigator should immediately brief him when he embarks. The pilot must know the ship's maneuvering characteristics before entering restricted waters. The briefing should cover, as a minimum, the following:

- **Detailed Coverage of the Track Plan:** Go over the planned route in detail. Use the prepared and approved chart as part of this brief. Concentrate especially on all the NAVAIDS and soundings which are being used to indicate danger. Cover the buoyage system in use and the port's major NAVAIDS. Point out the radar NAVAIDS for the radar operator. Often, a *Fleet Guide* or *Sailing Directions* will have pictures of a port's NAVAIDS. This is especially important for the piloting party that has never transited this particular port before. If no pictures are available, consider stationing a photographer to take some for submission to DMAHTC.

- **Harbor Communications:** Discuss the bridge-to bridge radio frequencies used to raise harbor control. Discuss what channel the vessel is supposed to monitor on its passage into port and the port's communication protocol.

- **Duties and Responsibilities:** Each member of the piloting team must have a thorough understanding of his duties and responsibilities. He must also understand how his part fits into the scheme of the whole.

The radar plotter, for example, must know if radar will be the primary or secondary source of fix information. The bearing recorder must know what fix interval the navigator is planning to use. Each person must be thoroughly briefed on his job; there is little time for questions once the vessel enters the channel.

805. Voyage Planning To The Harbor Entrance (Inbound Vessel Only)

The vessel's planned estimated time of arrival (ETA) at its moorings determines the vessel's course and speed to the harbor entrance. Arriving at the mooring site on time may be important in a busy port which operates its port services on a tight schedule. Therefore, it is important to conduct harbor approach voyage planning accurately. Take the ETA at the mooring and subtract from that the time it will take to navigate the harbor to the pier. The resulting time is when you must arrive at the harbor entrance. Next, measure the distance between the vessel's present location and the harbor entrance. Determine the speed of advance (SOA) the vessel will use to make the transit to the harbor. Use the distance to the harbor and the SOA to calculate what time to leave the present position to make the mooring ETA.

Consider these factors which might affect this decision:

- **Weather:** This is the single most important factor in harbor approach planning because it directly affects the vessel's SOA. The thicker the weather, the more slowly the vessel must proceed. Therefore, if heavy fog or rain is in the forecast, the navigator must advance the time he was planning to leave for the harbor entrance.

- **Mooring Procedures:** The navigator must take more than distance into account when calculating how long it will take him to pilot to his mooring. If the vessel needs a tug, that will significantly increase the time allotted to piloting. Similarly, picking up (inbound) or dropping off (outbound) a pilot adds time to the transit. It is better to allow a margin for error when trying to add up all the time delays caused by these procedures. It is always easier to avoid arriving early by slowing down than it is to make up lost time by speeding up.

- **Time to Find the Harbor Entrance:** Depending on the sophistication of his vessel's navigation suite, a navigator may require some time to find the harbor entrance. This is seldom a problem with warships and large merchant vessels, both of which carry sophisticated electronic navigation suites. However, it may be a consideration for the yachtsman relying solely on dead reckoning and celestial navigation.

- **Shipping Density:** Generally, the higher the shipping density entering and exiting the harbor, the longer it will take to proceed into the harbor entrance safely.

TRANSITION TO PILOTING

806. Stationing The Piloting Team

Approximately one hour prior to leaving port or entering restricted waters, station the piloting team. The number and type of personnel available for the piloting team depend on the vessel. A Navy warship, for example, has more people available for piloting than does a merchantman. Therefore, more than one of the jobs listed below may have to be filled by a single person. The piloting team should consist of:

- **The Captain:** The captain is ultimately responsible for the safe navigation of his vessel. His judgment regarding navigation is final. The piloting team acts to support the captain, advising him so he can make informed decisions on handling his vessel.

- **The Pilot:** The pilot is usually the only member of the piloting team not normally a member of the ship's company. Many ports require a pilot, a federal or state licensed navigator who possesses extensive local knowledge of the harbor, to be on board as the vessel makes its harbor passage. The piloting team must understand the relationship between the pilot and the captain. The pilot is perhaps the captain's most important navigation advisor; often, the captain will defer to his recommendations when navigating an unfamiliar harbor. The pilot, too, bears some responsibility for the safe passage of the vessel; he can be censured for errors of judgment which cause accidents. However, the presence of a pilot in no way relieves the captain of his ultimate responsibility for safe navigation. The piloting team works to support and advise the vessel's *captain*.

- **The Officer of the Deck (Conning Officer):** In Navy piloting teams, neither the pilot or the captain usually has the **conn**. The officer having the conn directs the ship's movements by rudder and engine orders. Another officer of the ship's company usually fulfills this function. The captain can take the conn immediately simply by issuing an order to the helm should an emergency arise. The conning officer of a merchant vessel can be either the pilot, the captain, or another watch officer. In any event, the officer having the conn must be clearly indicated in the ship's deck log at all times. Of-

ten a single officer will have the deck and the conn. However, sometimes a junior officer will take the conn for training. In this case, different officers will have the deck and the conn. The officer who retains the deck retains the responsibility for the vessel's safe navigation.

- **The Navigator:** The vessel's navigator is the officer directly responsible to the ship's captain for the safe navigation of the ship. He is the captain's principal navigation advisor. The piloting party works for him. He channels the required information developed by the piloting party to the ship's conning officer on recommended courses, speeds, and turns. He also carefully looks ahead for potential navigation hazards and makes appropriate recommendations. He is the most senior officer who devotes his effort exclusively to monitoring the navigation picture. The captain and the conning officer are concerned with all aspects of the passage, including contact avoidance and other necessary ship evolutions (making up tugs, maneuvering alongside a small boat for personnel transfers, engineering evolutions, and coordinating with harbor control via radio, for example). The navigator, on the other hand, focuses solely on safe navigation. It is his job to anticipate danger and keep himself appraised of the navigation situation at all times.

- **Bearing Plotting Team:** This team consists, ideally, of three persons. The first person measures the bearings. The second person records the bearings in an official record book. The third person plots the bearings. The more quickly and accurately this process is completed, the sooner the navigator has an accurate picture of the ship's position. The bearing taker should be an experienced individual who has traversed the port before and who is familiar with the NAVAIDS. He should take his round of bearings as quickly as possible, minimizing any time delay errors in the resulting fix. The plotter should also be an experienced individual who can quickly and accurately lay down the required bearings. The bearing recorder can be one of the junior members of the piloting team.

- **The Radar Operator:** The radar operator has one of the more difficult jobs of the team. The radar is as important for collision avoidance as it is for navigation. Therefore, this operator must "time share" the radar between these two functions. Determining the amount of time spent on these functions falls within the judgment of the captain and the navigator. If the day is clear and the traffic heavy, the captain may want to use the radar mostly for collision avoidance. As the weather worsens, obscuring visual NAVAIDS, the importance of radar for safe navigation increases. The radar operator must be given clear guidance on how the captain and navigator want the radar to be operated.

- **Plot Supervisors:** Ideally, the piloting team should consist of two plots: the primary plot and the secondary plot. The navigator should designate the type of navigation that will be employed on the primary plot. All other fix sources should be plotted on the secondary plot. For example, if the navigator designates visual piloting as the primary fix method, lay down only visual bearings on the primary plot. Lay down all other fix sources (radar, electronic, or satellite) on the secondary plot. The navigator can function as the primary plot supervisor. A senior, experienced individual should be employed as a secondary plot supervisor. The navigator should frequently compare the positions plotted on both plots as a check on the primary plot.

  There are three major reasons for maintaining a primary and secondary plot. First, as mentioned above, the secondary fix sources provide a good check on the accuracy of visual piloting. Large discrepancies between visual and radar positions may point out a problem with the visual fixes that the navigator might not otherwise suspect. Secondly, the navigator often must change the primary means of navigation during the transit. He may initially designate visual bearings as the primary fix method only to have a sudden storm or fog obscure the visual NAVAIDS. If he shifts the primary fix means to radar, he has a track history of the correlation between radar and visual fixes. Finally, the piloting team often must shift charts several times during the transit. When the old chart is taken off the plotting table and before the new chart is secured, there is a period of time when no chart is in use. Maintaining a secondary plot eliminates this complication. Ensure the secondary plot is not shifted prior to getting the new primary plot chart down on the chart table. In this case, there will always be a chart available on which to pilot. Do not consider the primary chart shifted until the new chart is properly secured and the plotter has transferred the last fix from the original chart onto the new chart.

- **Satellite Navigation Operator:** This operator normally works for the secondary plot supervisor. GPS absolute accuracy with SA operational is not sufficient for most piloting applications. However, the secondary plot should keep track of GPS fixes. If the teams looses visual bearings in the channel and no radar NAVAIDS are available, GPS may be the most accurate fix source available. The navigator must have some data on the comparison between satellite positions and visual positions over the history of the passage to use satellite positions effectively. The only way to obtain this data is to plot satellite positions and compare these positions to visual positions throughout the harbor passage.

- **Fathometer Operator:** Run the fathometer continuously and station an operator to monitor it. Do not rely on audible alarms to key your attention to this critically important piloting tool. The fathometer operator must

know the warning and danger soundings for the area the vessel is transiting. Most fathometers can display either total depth of water or depth under the keel. Set the fathometer to display depth under the keel. The navigator must check the sounding at each fix and compare that value to the charted sounding. A discrepancy between these values is cause for immediate action to take another fix and check the ship's position.

807. Plot Setup

Once the piloting team is on station, ensure the primary and secondary plot have the following instruments:

- **Dividers:** Dividers are used to measure distances between points on the chart.

- **Compasses:** Compasses are used to plot range arcs for radar LOP's. **Beam compasses** are used when the range arc exceeds the spread of a conventional compass. Both should be available at both plots.

- **Bearing Measuring Devices:** Several types of bearing measuring devices are available. The preferred device is the parallel motion plotter (PMP) used in conjunction with a drafting table. Otherwise, use parallel rulers or rolling rulers with the chart's compass rose. Finally, the plotter can use a one arm protractor. The plotter should use the device with which he can work the most quickly and accurately.

- **Sharpened Pencils and Erasers:** Ensure an adequate supply of pencils is available. There is generally not time to sharpen one if it breaks in the middle of the transit, so have several sharpened pencils available at the plot.

- **Three Arm Protractor:** This protractor is used to plot relative bearings and sextant horizontal angles should the true bearing source fail during the transit.

- **Fischer Radar Plotting Templates:** Fischer plotting is covered in Chapter 13. The plotting templates for this technique should be stacked near the radar repeater.

- **Time-Speed-Distance Calculator:** Given two of the three unknowns (between time, speed, and distance), this calculator allows for rapid computation of the third.

- **Tide and Current Graphs:** Post the tide and current graphs near the primary plot for easy reference during the transit. Give a copy of the graphs to the conning officer and the captain.

Once the navigator verifies the above equipment is in place, he tapes down the charts on the chart table. If more than one chart is required for the transit, tape the charts in a stack such that the plotter works from the top to the bottom of the stack. This minimizes the time required to shift the chart during the transit. If the plotter is using a PMP, align the arm of the PMP with any meridian of longitude on the chart. While holding the PMP arm stationary, adjust the PMP to read 000.0°T. This procedure calibrates the PMP to the chart in use. Perform this alignment every time the piloting team shifts charts.

Be careful not to fold under any important information when folding the chart on the chart table. Ensure the chart's distance scale, the entire track, and all important warning information are visible.

Energize and test all electronic navigation equipment, if not already in operation. This includes the radar and the GPS receiver. Energize and test the fathometer. Ensure the entire electronic navigation suite is operating properly prior to entering restricted waters.

808. Evolutions Prior To Piloting

The navigator should always accomplish the following evolutions prior to piloting:

- **Testing the Shaft on the Main Engines in the Astern Direction:** This ensures that the ship can answer a backing bell. If the ship is entering port, no special precautions are required prior to this test. If the ship is tied up at the pier preparing to get underway, exercise extreme caution to ensure no way is placed on the ship while testing the main engines.

- **Making the Anchor Ready for Letting Go:** Make the anchor ready for letting go and station a watchstander in direct communications with the bridge at the anchor windlass. Be prepared to drop anchor immediately when piloting if required to keep from drifting too close to a navigation hazard.

- **Calculate Gyro Error:** An error of greater than 1.0° T indicates a gyro problem which should be investigated prior to piloting. There are several ways to determine gyro error:

    1. Compare the gyro reading with a known accurate heading reference such as an inertial navigator. The difference in the readings is the gyro error.

    2. Mark the bearing of a charted range as the range NAVAID's come into line and compare the gyro bearing with the charted bearing. The difference is the gyro error.

    3. Prior to getting underway, plot a dockside fix using

at least three lines of position. The three LOP's should intersect at a point. Their intersecting in a "cocked hat" indicates a gyro error. Incrementally adjust each visual bearing by the same amount and in the same direction until the fix plots as a pinpoint. The total corretion required to eliminate the cocked hat is the gyro error.

4. Measure a celestial body's azimuth, a celestial body's amplitude, or Polaris' azimuth with the gyro, and then compare the measured value with a value computed from the *Sight Reduction* tables or the *Nautical Almanac*. These methods are covered in detail in Chapter 17.

Report the magnitude and direction of the gyro error to the navigator and captain. The direction of the error is determined by the relative magnitude of the gyro reading and the value against which it is compared. When the compass is *least*, the error is *east*. Conversely, when the compass is *best*, the error is *west.*

809. Records

Ensure the following records are assembled and personnel assigned to complete them prior to piloting:

- **Bearing Record Book:** The bearing recorders for the primary and secondary plots should record all the bearings used on their plot during the entire transit. The books should clearly list what NAVAIDS are being used and what method of navigation was being used on their plot. In practice, the primary bearing book will contain mostly visual bearings and the secondary bearing book will contain mostly radar ranges and bearings.

- **Fathometer Log:** In restricted waters, monitor soundings continuously and record soundings every five minutes in the fathometer log. Record all fathometer settings that could affect the sounding display.

- **Deck Log:** This log is the legal record of the passage. Record all ordered course and speed changes. Record all the navigator's recommendations and whether the navigator concurs with the actions of the conning officer. Record all buoys passed, and the shift between different Rules of the Road. Record the name and embarkation of any pilot. Record who has the conn at all times. Record any casualty or important event. The deck log combined with the bearing log should constitute a complete record of the passage.

810. Harbor Approach (Inbound Vessels Only)

The piloting team must make the transition from coastal navigation to piloting smoothly as the vessel approaches restricted waters. There is no rigid demarcation between coastal navigation and piloting. Often visual NAVAIDS are visible miles from shore where hyperbolic and satellite navigation provides sufficient absolute accuracy to ensure ship safety. The navigator should take advantage of this overlap when approaching the harbor. Plot hyperbolic, satellite, and visual fixes concurrently on the primary plot, ensuring the piloting team has correctly identified NAVAIDS and is comfortably settling into a piloting routine. Once the vessel is close enough to the shore such that sufficient NAVAIDS (at least three with sufficient bearing spread) become visible, the navigator should order visual bearings only for the primary plot and shift plotting all other fixes to the secondary plot.

Take advantage of the coastal navigation and piloting overlap to shorten the fix interval gradually. The navigator must use his judgment in adjusting these transition fix intervals. If the ship is steaming inbound directly towards the shore, set a fix interval such that two fix intervals lie between the vessel and the nearest danger. Prior to entering into restricted waters, the piloting team should be plotting visual fixes at three minute intervals.

FIXING A VESSEL'S POSITION WHILE PILOTING

The navigator now has his charts prepared; his team briefed, equipped, and on station; his equipment tested; and his record books distributed. He is now ready to begin piloting.

Safe navigation while piloting requires frequent fixing of the ship's position. The next sections will discuss the three major methodologies used to fix a ship's position when piloting: crossing lines of position, copying satellite or Loran data, or advancing a single line of position. Using one method does not exclude using other methods. The navigator must obtain as much information as possible and employ as many of these methods as practical while piloting.

811. Fixing The Ship's Position By Two Or More Lines Of Position

The intersection of at least two LOP's constitutes a **fix**. However, always use three LOP's if three are available. Some of the most commonly used methods of obtaining LOP's are discussed below:

- **Fix by Two Bearing Lines:** The plotter lays down two or more bearing lines from charted NAVAIDS. This is the most common and often the most accurate way to fix a vessel's position. The plotter can also lay down

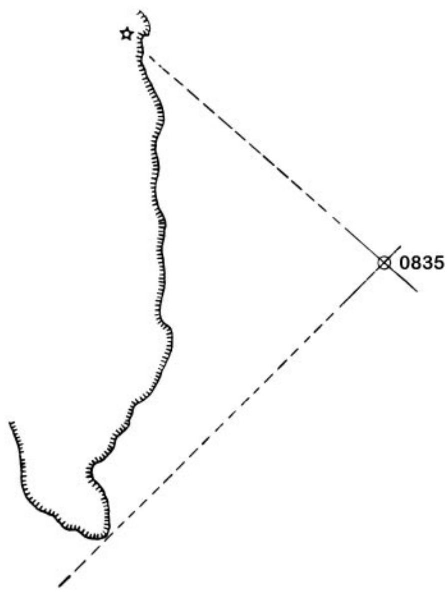


Figure 811a. A fix by two bearing lines.

bearings to a NAVAID and a bearing to the tangent of a body of land. See Figure 811a. The intersection of these lines constitutes a fix. Plotting bearing lines from charted buoys is the least preferred method of fixing by two bearing lines because the buoy's charted position is only approximate. Tangent LOPs to land areas must be taken carefully to get an accurate line, particularly at long ranges; charted NAVAIDS are preferred.

- **Fix by Two Ranges:** The navigator can plot a fix consisting of the intersection of two range arcs from charted objects. He can obtain an object's range in several ways:

1. Radar Ranges: See Figure 811b. The plotter lays down a range arc from a small island and a range arc from a prominent point on shore. The intersection of the range arcs constitutes a fix. The navigator can plot ranges from any point on the radar scope which he can correlate on his chart. This is the most convenient and accurate way to obtain an object's range. If a choice is available between fixed radar NAVAIDS and low lying land, choose the fixed NAVAID. This will minimize errors caused by using low lying land subject to large tidal ranges.

2. Stadimeter Ranges: Given a known height of a NAVAID, use a stadimeter to determine the range. Though most often used to determine the distance to a surface contact, a stadimeter can be used to determine an object's range. See Figure 811c for a representation of the geometry involved. Generally, stadimeters contain a height scale on which is set the height of the object. The observer then directs his line of sight through the stadimeter to the base of the object being observed. Finally, he adjusts the stadimeter's range index until the object's top reflection is "brought down" to the visible horizon. Read the object's range off of the stadimeter's range index.

3. Sextant Vertical Angles: Measure the vertical angle from the top of the NAVAID to the waterline below the NAVAID. Enter Table 16 to determine the distance of the NAVAID. The navigator must

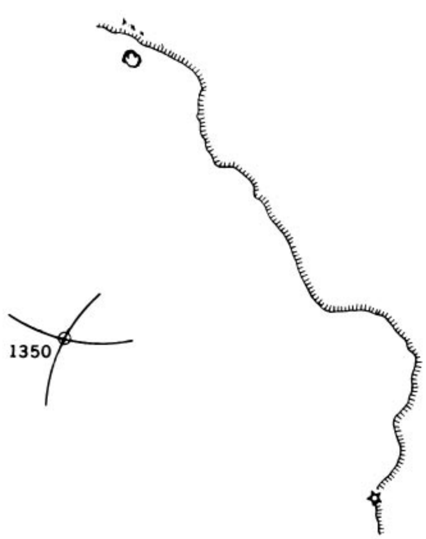


Figure 811b. A fix by two radar ranges.

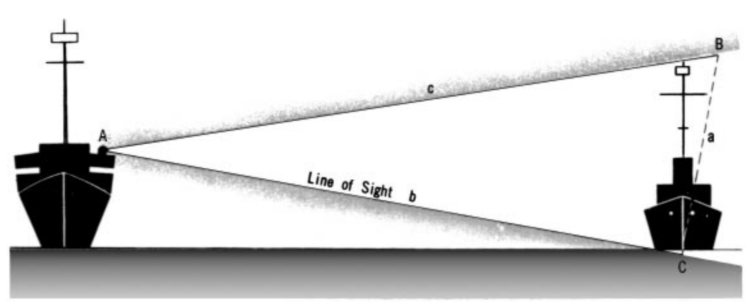


Figure 811c. Principle of stadimeter operation.

know the height of the NAVAID above sea level to use this table; it can be found in the light list.

4. Sonar Ranges: If the vessel is equipped with a sonar suite, the navigator can use sonar echoes to determine ranges to charted underwater objects. It may take some trial and error to set the active signal strength at a value that will give a enough strong return and still not cause excessive reverberation. Check local harbor restrictions on energizing active sonar. Avoid active sonar transmissions in the vicinity of divers.

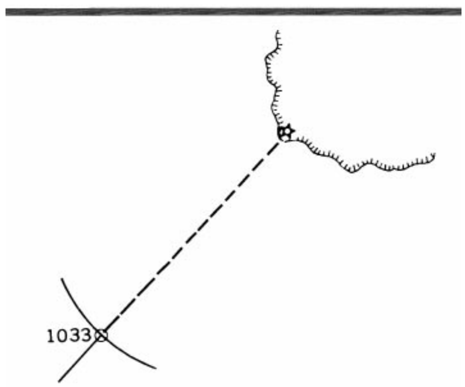


Figure 811d. A fix by range and bearing of a single object.

- **Fix at Intersection of Bearing Line and Range:** This is a hybrid fix of LOP's from a bearing and range to a single object. The radar is the only instrument that can give simultaneous range and bearing information to the same object. (A sonar system can also provide bearing and range information, but sonar bearings are far too inaccurate to use in piloting.) Therefore, with the radar, the navigator can obtain an instantaneous fix from only one NAVAID. This unique fix is shown in Figure 811d. This makes the radar an extremely useful tool for the piloting team. The radar's characteristics make it much more accurate determining range than determining bearing; therefore, two radar ranges are preferable to a radar range and bearing.

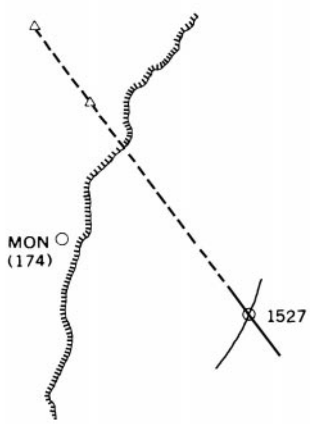


Figure 811e. A fix by a range and distance.

- **Fix by Range and Distance:** When the vessel comes in line with a range, plot the bearing to the range and cross this LOP with a distance from another NAVAID. Figure 811e shows this fix.

812. Fixing The Ship's Position By Electronics

The stated absolute accuracy of GPS subjected to SA is insufficient to ensure ship's safety while piloting. However, the navigator should not ignore satellite positions. If the vessel is a U.S. Navy warship, the navigator will have access to the Precise Positioning Service (PPS). Even if the navigator does not have access to the PPS, routinely comparing visual and satellite positions provides the navigator some information to use in case he loses both radar and visual piloting. When poor visibility precludes using visual NAVAID's and the area is not suitable for radar piloting, having a satellite position and some idea of how it has related to previous visual fixes is important. The satellite positions should be plotted periodically on the secondary plot.

If the navigator has access to Differential GPS, the absolute accuracy of his satellite positions may be high enough to provide an even more meaningful backup to visual and radar piloting.

Loran C, while generally not suitable for piloting in terms of absolute accuracy, is often accurate enough in terms of repeatable accuracy. Therefore Loran readings should be monitored in case other systems fail.

813. The Running Fix

When only one NAVAID is available from which to obtain bearings, use a technique known as the **running fix**. Use the following methodology:

1. Plot a bearing to a NAVAID (LOP 1).
2. Plot a second bearing to a NAVAID (either the same NAVAID or a different one) at a later time (LOP 2).
3. Advance LOP 1 to the time when LOP 2 was taken.
4. The intersection of LOP 2 and the advanced LOP 1 constitute the running fix.

Figure 813a represents a ship proceeding on course 020°, speed 15 knots. At 1505, the plotter plots an LOP to a lighthouse bearing 310°. The ship can be at any point on this 1505 LOP. Some possible points are represented

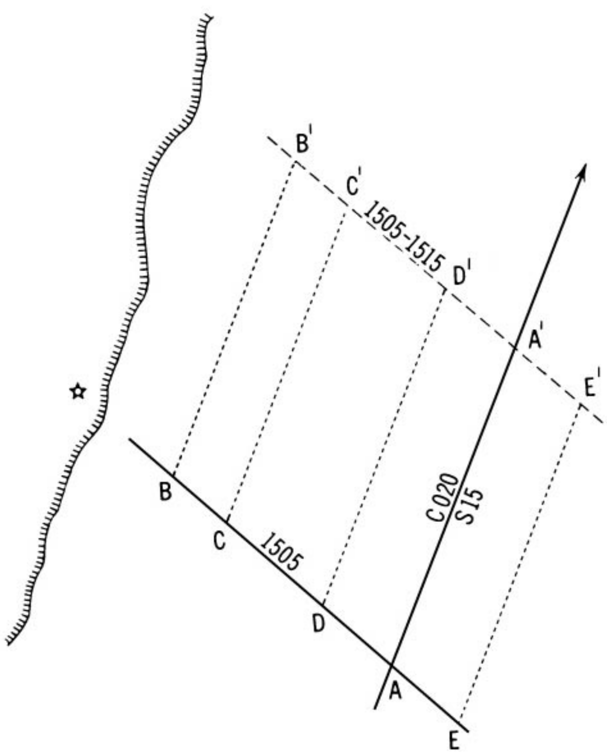


Figure 813a. Advancing a line of position.

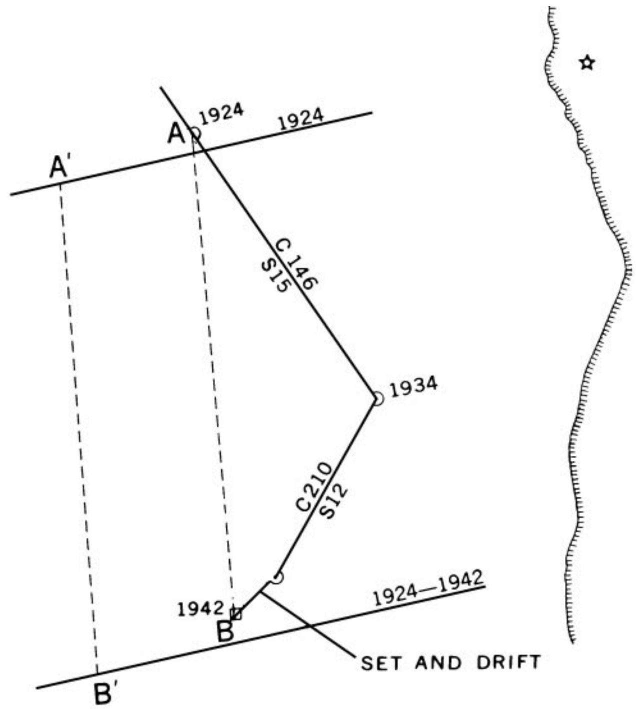


Figure 813b. Advancing a line of position with a change in course and speed, allowing for set and drift.

as points A, B, C, D, and E in Figure 813a. Ten minutes later the ship will have traveled 2.5 miles in direction 020°. If the ship was at A at 1505, it will be at A' at 1515. However, if the position at 1505 was B, the position at 1515 will be B'. A similar relationship exists between C and C', D and D', E and E'. Thus, if any point on the original LOP is moved a distance equal to the distance run in the direction of the motion, a line through this point parallel to the original line of position represents all possible positions of the ship at the later time. This process is called **advancing** a line of position. Moving a line back to an earlier time is called **retiring** a line of position.

When advancing a line of position, consider course changes, speed changes, and set and drift between the two bearing lines. Three methods of advancing an LOP are discussed below:

Method 1: See Figure 813a. To advance the 1924 LOP to 1942, first apply the best estimate of set and drift to the 1942 DR position and label the resulting position point B. Then, measure the distance between the dead reckoning position at 1924 (point A) and point B. Advance the LOP a distance equal to the distance between points A and B. Note that LOP A'B' is in the same direction as line AB.

Method 2: See Figure 813c. Advance the NAVAIDS position on the chart for the course and distance traveled by the vessel and draw the line of position from the NAVAIDS advanced position. This is the most satisfactory method for advancing a circle of position.

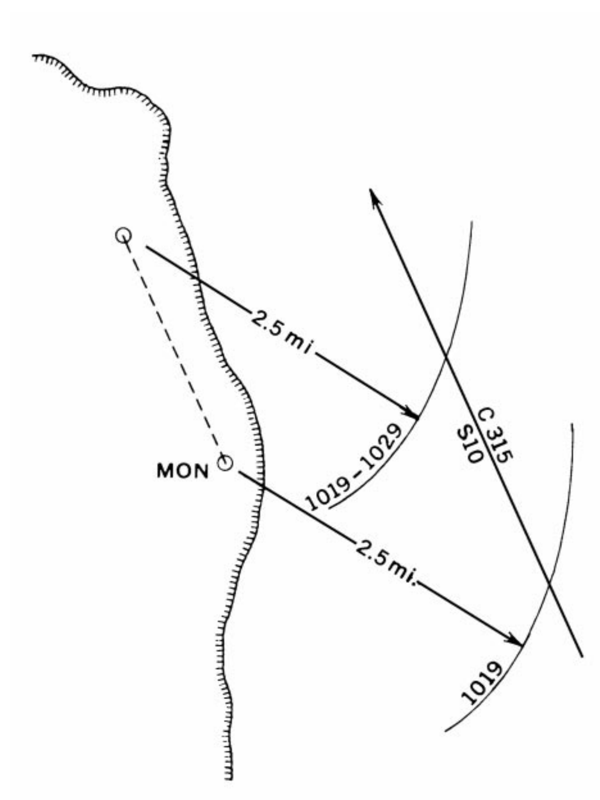


Figure 813c. Advancing a circle of position.

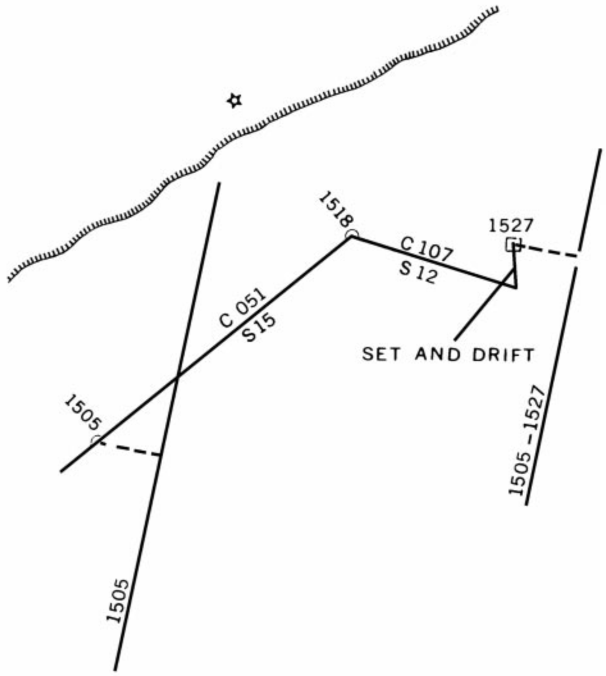


Figure 813d. Advancing a line of position by its relation to the dead reckoning.

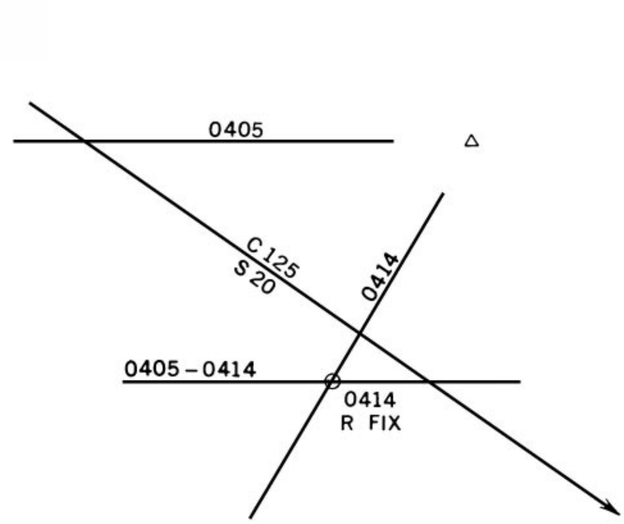


Figure 813e. A running fix by two bearings on the same object.

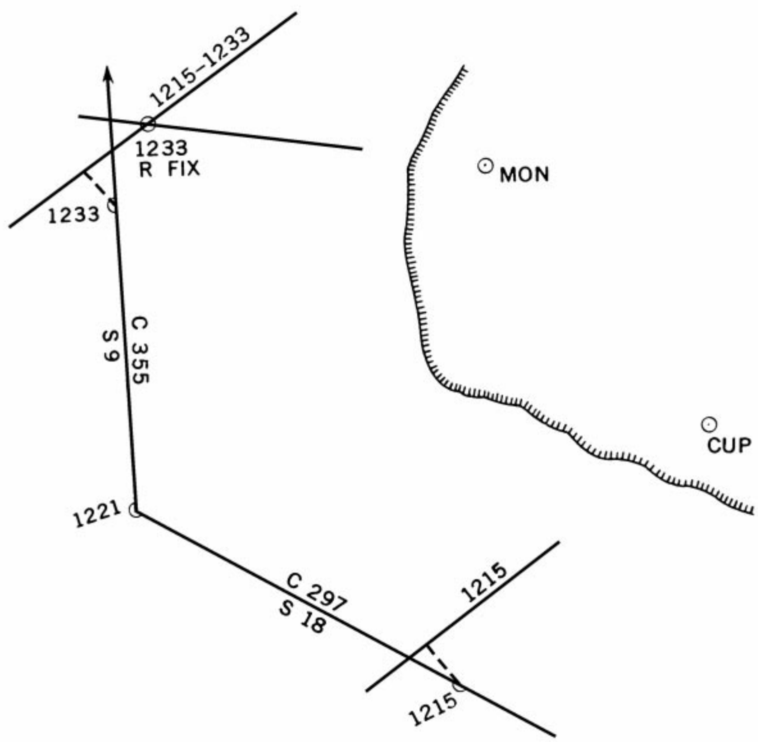


Figure 813f. A running fix with a change of course and speed between observations on separate landmarks.

Method 3: See Figure 813d. To advance the 1505 LOP to 1527, first draw a correction line from the 1505 DR position to the 1505 LOP. Next, apply a set and drift correction to the 1527 DR position. This results in a 1527 estimated position (EP). Then, draw from the 1527 EP a correction line of the same length and direction as the one drawn from the 1505 DR to the 1505 LOP. Finally, parallel the 1505 bearing to the end of the correction line as shown.

Label an advanced line of position with both the time of observation and the time to which the line is adjusted.

Figure 813e through Figure 813g demonstrate three separate running fixes. Figure 813e illustrates the case of obtaining a running fix with no change in course or speed between taking two bearings on the same NAVAID. Figure 813f illustrates a running fix with changes in a vessel's course and speed between its taking two bearings on two different objects. Finally, Figure 813g illustrates a running fix obtained by advancing range circles of position using the second method discussed above.

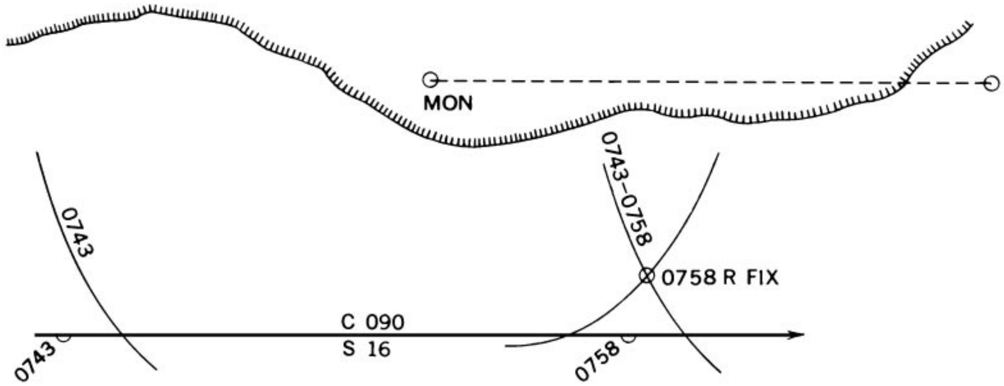


Figure 813g. A running fix by two circles of position.

PILOTING PROCEDURES

The previous section discussed the methods for fixing the ship's position. This section discusses integrating the fix methods discussed above and the use of the fathometer into a piloting procedure. The navigator must develop his piloting procedure to meet several requirements. He must obtain all available information from as many sources as possible. He must plot and evaluate this information. Finally, he must relay his evaluations and recommendations to the vessel's conning officer. This section examines some considerations to ensure the navigator accomplishes all these requirements quickly and effectively.

814. Fix Type And Fix Interval

The preferred piloting fix type is visual bearings from charted shore-based NAVAIDS. Plot visual bearings on the primary plot and plot all other fixes on the secondary plot. If poor visibility obscures visual NAVAIDS, shift to radar piloting on the primary plot. If neither visual or radar piloting is available, consider standing off until the visibility improves.

The interval between fixes in restricted waters should not exceed three minutes. Setting the fix interval at three minutes optimizes the navigator's ability to assimilate and evaluate all available information. A navigator must not only receive and plot positioning information, but he must also evaluate the information. He must relate it to charted navigation hazards and to his vessel's intended track. It should take a well trained plotting team no more than 30 seconds to measure, record, and plot three bearings to three separate NAVAIDS. The navigator should spend the majority of the fix interval time interpreting the information, evaluating the navigation situation, and making recommendations to the conning officer.

If three minutes goes by without a fix, inform the captain and try to plot a fix as soon as possible. If the delay was caused by a loss of visibility, shift to radar piloting. If the delay was caused by plotting error, take another fix. If the navigator cannot get a fix down on the plot for several more minutes, consider slowing or stopping the ship until its position can be fixed. Never continue a passage through restricted waters if the vessel's position is uncertain.

The secondary plot supervisor should maintain the same fix interval as the primary plot. Usually, this means he should plot a radar fix every three minutes. He should plot other fix sources (sonar ranges and satellite fixes, for example) at an interval sufficient for making meaningful comparisons between fix sources. Every third fix interval,

he should pass a radar fix to the primary plot for comparison with the visual fix. He should inform the navigator how well all the fix sources plotted on the secondary plot are tracking.

815. The Cyclic Routine

Following the cyclic routine ensures the timely and efficient processing of data. It yields the basic information which the navigator needs to make informed recommendations to the conning officer and captain.

Repeat this cyclic routine at each fix interval beginning when the ship gets underway until it clears the harbor (outbound) or when the ship enters the harbor until it is moored (inbound).

The cyclic routine consists of the following steps, modified as discussed below for approaching a turn:

1. Plotting the fix.
2. Labeling the fix.
3. Dead Reckoning two fix intervals ahead of the fix.
4. Calculating the set and drift from the DR and fix.

- **Plotting the Fix:** This involves coordination between the bearing taker, recorder, and plotter. The bearing taker must measure his bearings as quickly as possible. As quickly as he takes them, however, there will be a finite amount of time between the first and last bearing measured. The navigator should advance the first and second LOP's to the time of the last bearing taken and label the last bearings time as the fix time. Try to have the fix completed on the even minute to allow for meaningful comparison with the DR.

- **Labeling the Fix:** The plotter should clearly mark a visual fix with a circle or an electronic fix with a triangle. Clearly label the time of each fix. A visual running fix should be circled, marked "R Fix" and labeled with the time of the second LOP. Maintain the chart neat and uncluttered when labeling fixes.

- **Dead Reckoning Two Fix Intervals Ahead:** After labeling the fix, the plotter should dead reckon the fix position ahead two fix intervals. The navigator should carefully check the area marked by this DR for any navigation hazards. If the ship is approaching a turn, update the turn bearing as discussed in section 801.

- **Calculate Set and Drift at Every Fix:** Calculating set and drift is covered in Chapter 7. Calculate these values at every fix and inform the captain and conning officer. Compare the actual values of set and drift with the predicted values from the current graph discussed in section 802 above. Evaluate how the current is affecting the vessel's position in relation to the track and recommend courses and speeds to regain the planned track. Because the navigator can determine set and drift only when comparing fixes and DR's plotted for the same time, ensure that fixes are taken at the times for which a DR has been plotted. Repeat this cyclic routine at each fix interval beginning when the ship gets underway until it clears the harbor (outbound) or when the ship enters the harbor until she is moored (inbound).

- **Cyclic Routine When Turning:** Modify the cyclic routine slightly when approaching a turn. Adjust the fix interval so that the plotting team has a fix plotted approximately one minute before a scheduled turn. This gives the navigator sufficient time to evaluate the position in relation to the planned track, DR ahead to the slide bar to determine a new turn bearing, relay the new turn bearing to the conning officer, and then monitor the turn bearing to mark the turn.

Approximately 30 seconds before the time to turn, train the bearing measurement instrument on the turn bearing NAVAID. The navigator should watch the bearing of the NAVAID approach the turn bearing. Approximately 1° away from the turn bearing, announce to the conning officer: "Stand by to turn." Slightly before the turn bearing is indicated, report to the conning officer: "Mark the turn." Make this report slightly before the bearing is reached because it takes the conning officer a finite amount of time to acknowledge the report and order the helmsman to put over the rudder. Additionally, it takes a finite amount of time for the helmsman to turn the rudder and for the ship to start to turn. If the navigator waits until the turn bearing is indicated to report the turn, the ship will turn too late.

Once the ship is steady on the new course, immediately take another fix to evaluate the vessel's position in relation to the track. If the ship is not on the track after the turn, recommend a course to the conning officer to regain track.

816. Using The Fathometer

Use the fathometer to determine whether the depth of water under the keel is sufficient to prevent the ship from grounding and to check the actual water depth with the charted water depth at the fix position. The navigator must compare the charted sounding at every fix position with the fathometer reading and report to the captain any discrepancies. Continuous soundings in pilot waters are mandatory.

See the discussion of calculating the warning and danger soundings in section 801. If the warning sounding is received, then slow the ship, fix the ship's position more frequently, and proceed with extreme caution. Ascertain immediately where the ship is in the channel; if the minimum expected sounding was noted correctly, the warning sounding indicates the vessel may be leaving the channel and standing into shoal water. Notify the vessel's captain and conning officer immediately.

If the danger sounding is received, take immediate action to get the vessel back to deep water. Reverse the engines and stop the vessel's forward movement. Turn in the direction of

the deepest water before the vessel looses steerageway. Consider dropping the anchor to prevent the ship from drifting aground. The danger sounding indicates that the ship has left the channel and is standing into immediate danger. It requires immediate corrective action by the ship's conning officer, navigator, and captain to avoid disaster.

Many underwater features are poorly surveyed. If a fathometer trace of a distinct underwater feature can be obtained along with accurate position information, send the fathometer trace and related navigation data to the Defense Mapping Agency for entry into the Digital Bathymetric Data Base. See Chapter 30 for details on recording and reporting procedures.

ANCHORING PROCEDURES

817. Anchoring

If a vessel is to anchor at a predetermined point, such as in an assigned berth, follow an established procedure to ensure an accurate positioning of the anchor. The following procedure is representative. See Figure 817.

Locate the selected anchoring position on the chart. Consider limitations of land, current, shoals, other vessels when determining the direction of approach. Where conditions permit, make the approach heading into the current. Close observation of any other anchored vessels will provide clues as to which way the ship will lie to her anchor. If wind and current are strong and from different directions, ships will lie to their anchors according to the balance between these two forces and the draft and trim of each ship. Different ships may lie at different headings in the same anchorage depending on the balance of forces affecting them.

Approach from a direction with a prominent NAVAID, preferably a range, available dead ahead to serve as a steering guide. If practicable, use a straight approach of at least 1200 yards to permit the vessel to steady on the required course. Draw in the approach track, allowing for advance and transfer during any turns. In Figure 817, the chimney was selected as this steering bearing.

Next, draw a circle with the selected position of the anchor as the center, and with a radius equal to the distance

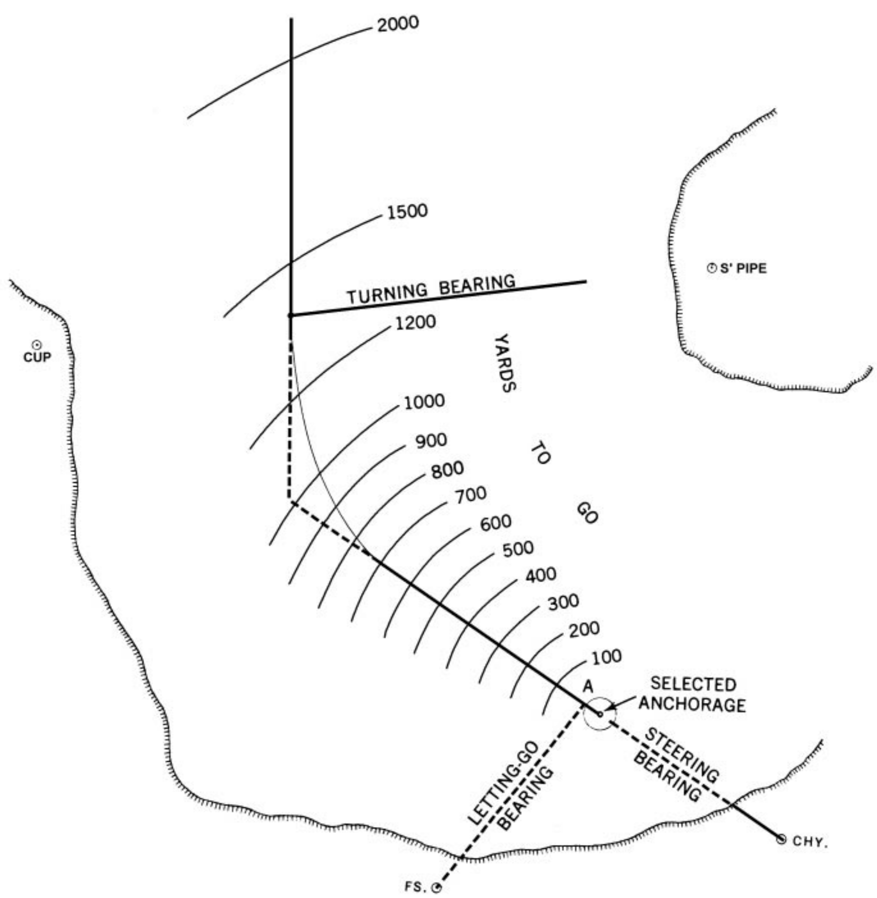


Figure 817. Anchoring.

between the hawsepipe and pelorus, alidade, or periscope used for measuring bearings. This circle is marked “A” in Figure 817. The intersection of this circle and the approach track is the position of the vessel’s bearing-measuring instrument at the moment of letting the anchor go. Select a NAVAID which will be on the beam when the vessel is at the point of letting go the anchor. This NAVAID is marked “FS” in Figure 817. Determine what the bearing to that object will be when the ship is at the drop point and measure this bearing to the nearest 0.1°T. Label this bearing as the letting go bearing.

During the approach to the anchorage, plot fixes at frequent intervals. The navigator must advise the conning officer of any tendency of the vessel to drift from the desired track. The navigator must frequently report the conning officer of the distance to go, permitting adjustment of the speed so that the vessel will be dead in the water or have very slight sternway when the anchor is let go. To aid in determining the distance to the drop point, draw and label a number of range arcs as shown in Figure 817 representing distances to go to the drop point.

At the moment of letting the anchor go, take a fix and plot the vessel’s exact position on the chart. This is important in the construction of the swing and drag circles discussed below. To draw these circles accurately, determine the position of the vessel at the time of letting go the anchor as accurately as possible.

Veer the anchor chain to a length equal to five to seven times the depth of water at the anchorage. The exact amount to veer is a function of both vessel type and severity of weather expected at the anchorage. When calculating the scope of anchor chain to veer, take into account the maximum height of tide.

Once the ship is anchored, construct two separate circles around the ship’s position when the anchor was dropped. These circles are called the **swing circle** and the **drag circle**. Use the swing circle to check for navigation hazards and use the drag circle to ensure the anchor is holding.

The swing circle’s radius is equal to the sum of the ship’s length and the scope of the anchor chain released. This represents the maximum arc through which a ship can swing while riding at anchor if the anchor holds. Examine this swing circle carefully for navigation hazards, interfering contacts, and other anchored shipping. Use the lowest height of tide expected during the anchoring period when checking inside the swing circle for shoal water.

The drag circle’s radius equals the sum of the hawsepipe to pelorus distance and the scope of the chain released. Any bearing taken to check on the position of the ship should, if the anchor is holding, fall within the drag circle. If a fix falls outside of that circle, then the anchor is dragging.

In some cases, the difference between the radii of the swing and drag circles will be so small that, for a given chart scale, there will be no difference between the circles when plotted. If that is the case, plot only the swing circle and treat that circle as both a swing and a drag circle. On the other hand, if there is an appreciable difference in radii between the circles when plotted, plot both on the chart. Which method to use falls within the sound judgment of the navigator.

When determining if the anchor is holding or dragging, the most crucial period is immediately after anchoring. Fixes should be taken frequently, at least every three minutes, for the first thirty minutes after anchoring. The navigator should carefully evaluate each fix to determine if the anchor is holding. If the anchor is holding, the navigator can then increase the fix interval. What interval to set falls within the judgment of the navigator, but the interval should not exceed 30 minutes.

818. Choosing An Anchorage

Most U.S. Navy vessels receive instructions in their movement orders regarding the choice of anchorage. Merchant ships are often directed to specific anchorages by harbor authorities. However, lacking specific guidance, the mariner should choose his anchoring positions using the following criteria:

- **Depth of Water:** Choose an area that will provide sufficient depth of water through an entire range of tides. Water too shallow will cause the ship to go aground, and water too deep will allow the anchor to drag.
- **Type of Bottom:** Choose the bottom that will best hold the anchor. Avoid rocky bottoms and select sandy or muddy bottoms if they are available.
- **Proximity to Navigation Hazards:** Choose an anchorage as far away as possible from known navigation hazards.
- **Proximity to Adjacent Ships:** Try to anchor as far away as possible from adjacent vessels.
- **Proximity to Harbor Traffic Lanes:** Do not anchor in a traffic lane.
- **Weather:** Choose the area with the weakest winds and currents.
- **Availability of NAVAIDS:** Choose an anchorage with several NAVAIDS available for monitoring the ship’s position when anchored.

NAVIGATIONAL ASPECTS OF SHIP HANDLING

819. Effects Of Banks, Channels, And Shallow Water

A ship moving through shallow water experiences pronounced effects from the proximity of the nearby bottom. Similarly, a ship in a channel will be affected by the proximity of the sides of the channel. These effects can easily cause errors in piloting which lead to grounding. The effects are known as **squat**, **bank cushion**, and **bank suction**. They are more fully explained in texts on shiphandling, but certain navigational aspects are discussed below.

Squat is caused by the interaction of the hull of the ship, the bottom, and the water between. As a ship moves through shallow water, some of the water it displaces rushes under the vessel to rise again at the stern. This causes a venturi effect, decreasing upward pressure on the hull. Squat makes the ship sink deeper in the water than normal and slows the vessel. The faster the ship moves through shallow water, the greater is this effect; groundings on both charted and uncharted shoals and rocks have occurred because of this phenomenon, when at reduced speed the ship could have safely cleared the dangers. When navigating in shallow water, the navigator must reduce speed to avoid squat. If bow and stern waves nearly perpendicular the direction of travel are noticed, and the vessel slows with no change in shaft speed, squat is occurring. Immediately slow the ship to counter it. Squatting occurs in deep water also, but is more pronounced and dangerous in shoal water. The large waves generated by a squatting ship also endanger shore facilities and other craft.

Bank cushion is the effect on a ship approaching a steep underwater bank at an oblique angle. As water is forced into the narrowing gap between the ship's bow and the shore, it tends to rise or pile up on the landward side, causing the ship to sheer away from the bank.

Bank suction occurs at the stern of a ship in a narrow channel. Water rushing past the ship on the landward side exerts less force than water on the opposite or open water side. This effect can actually be seen as a difference in draft readings from one side of the vessel to the other. The stern of the ship is forced toward the bank. If the ship gets too close to the bank, it can be forced sideways into it. The same effect occurs between two vessels passing close to each other.

These effects increase as speed increases. Therefore, in shallow water and narrow channels, navigators should decrease speed to minimize these effects. Skilled pilots may use these effects to advantage in particular situations, but the average mariner's best choice is slow speed and careful attention to piloting.

ADVANCED PILOTING TECHNIQUES

820. Assuming Current Values To Set Safety Margins When Using Running Fixes

Current affects the accuracy of a running fix. Consider, for example, the situation of an unknown head current. In Figure 820a, a ship is proceeding along a coast, on course 250 ° speed 12 knots. At 0920 light A bears 190°, and at 0930 it bears 143°. If the earlier bearing line is advanced a distance of 2 miles (10 minutes at 12 knots) in the direction of the course, the running fix is as shown by the solid lines. However, if there is a head current of 2 knots, the ship is making good a speed of only 10 knots, and in 10 minutes will travel a distance of only 1 $^{2}/_{3}$ miles. If the first bearing line is advanced this distance, as shown by the broken line, the actual position of the ship is at B. This actual position is nearer the NAVAID than the running fix actually plotted. A following current, conversely, would show a position too far from the NAVAID from which the bearing was measured.

If the navigator assumes a following current when advancing his LOP, the resulting running fix will plot further from the NAVAID than the vessel's actual position. Conversely, if he assumes a head current, the running fix will plot closer to the NAVAID than the vessel's actual position.To ensure a margin of safety when plotting running fix bearings to a NAVAID on

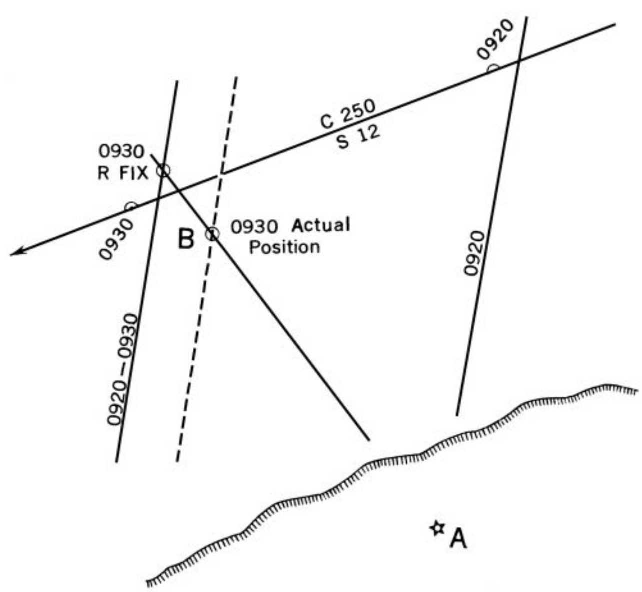


Figure 820a. Effect of a head current on a running fix.

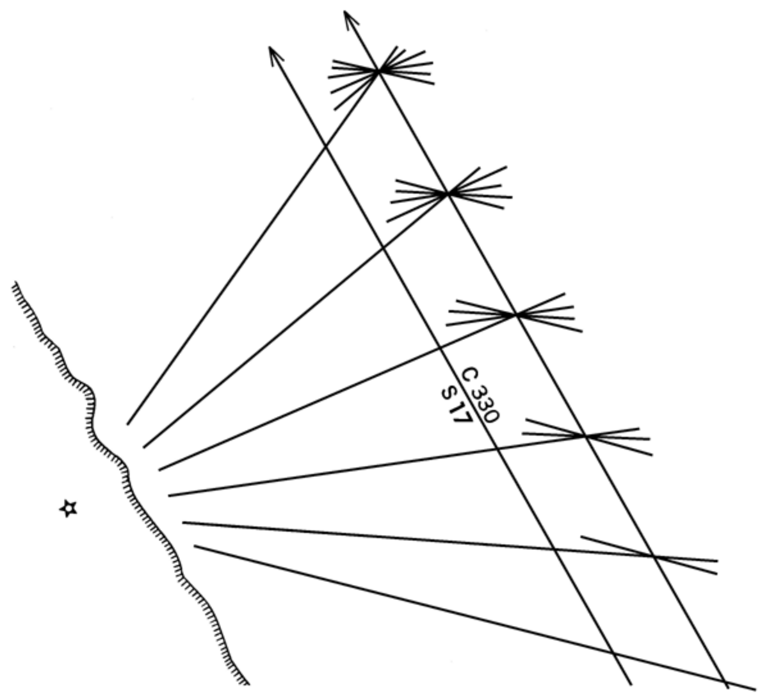


Figure 820b A number of running fixes with a following current.

shore, always assume the current slows a vessel's speed over ground. This will cause the running fix to plot closer to the shore than the ship's actual position.

When taking the second running fix bearing from a different object, maximize the speed estimate if the second object is on the same side and farther forward, or on the opposite side and farther aft, than the first object was when observed.

All of these situations assume that danger is on the same side as the object observed first. If there is either a head or following current, a series of running fixes based upon a number of bearings of the same object will plot in a straight line parallel to the course line, as shown in Figure 820b. The plotted line will be too close to the object observed if there is a head current and too far out if there is a following current. The existence of the current will not be apparent unless the actual speed over the ground is known. The position of the plotted line relative to the dead reckoning course line is not a reliable guide.

821. Determining Track Made Good By Plotting Running Fixes

A current oblique to a vessel's course will also result in an incorrect running fix position. An oblique current can be detected by observing and plotting several bearings of the same object. The running fix obtained by advancing one bearing line to the time of the next one will not agree with the running fix obtained by advancing an earlier line. See Figure 821a. If bearings A, B, and C are observed at five-minute intervals, the running fix obtained by advancing B to the time of C will not be the same as that obtained by advancing A to the time of C, as shown in Figure 821a.

Whatever the current, the navigator can determine the direction of the track made good (assuming constant current and constant course and speed). Observe and plot three bearings of a charted object O. See Figure 821b. Through O draw XY in any direction. Using a convenient scale, determine points A and B so that OA and OB are proportional to the time intervals between the first and second bearings and the second and third bearings, respectively. From A and B draw lines parallel to the second bearing line, intersecting the first and third bearing lines at C and D, respectively. The direction of the line from C and D is the track made good.

The distance of the line CD in Figure 821b from the track is in error by an amount proportional to the ratio of the speed made good to the speed assumed for the solution. If a good fix (not a running fix) is obtained at some time before the first bearing for the running fix, and the current has not changed, the track can be determined by drawing a line from the fix, in the direction of the track made good. The intersection of the track with any of the bearing lines is an actual position.

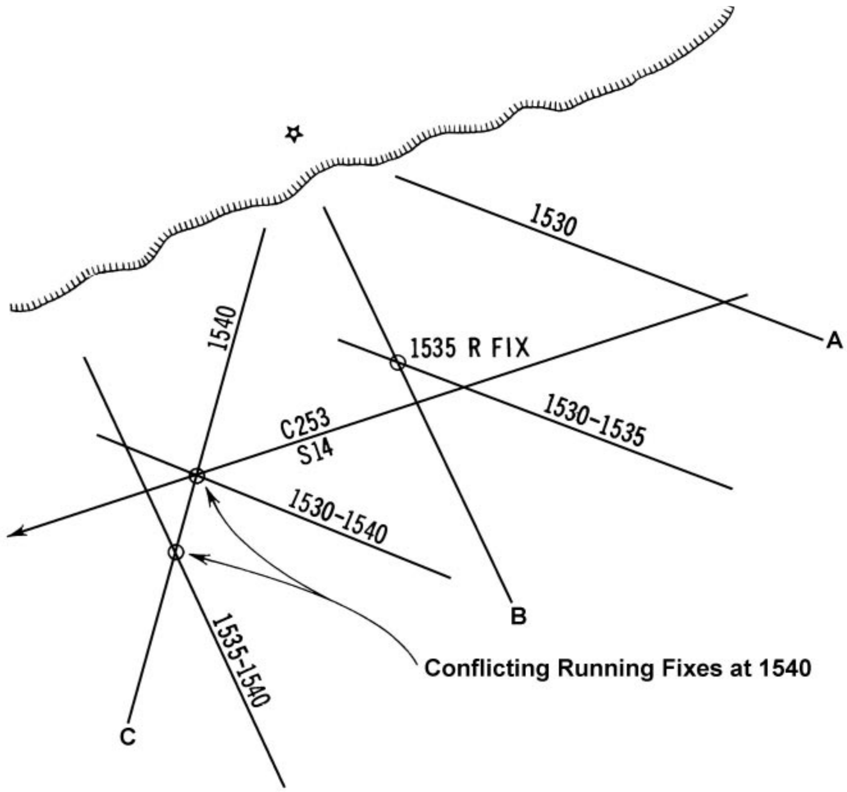


Figure 821a. Detecting the existence of an oblique current, by a series of running fixes.

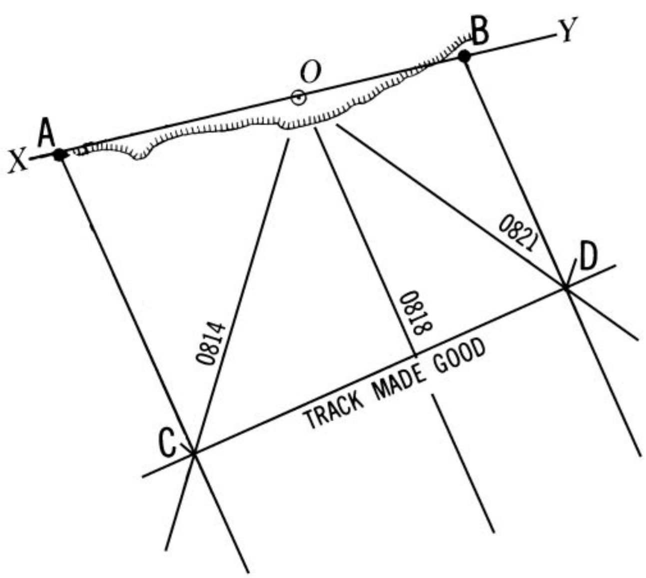


Figure 821b. Determining the track made good.

822. A Fix By The Distance Of An Object By Two Bearings (Table 18)

Geometrical relationships can define a running fix. In Figure 822, the navigator takes a bearing on NAVAID D. Express the bearing as degrees right or left of course. Later, at B, take a second bearing to D; similarly, take a bearing at C, when the landmark is broad on the beam. The navigator knows the angles at A, B, and C and the distance run between points. The various triangles can be solved using Table 18. From this table, the navigator can calculate the lengths of segments AD, BD, and CD. He knows the range and bearing; he can then plot an LOP. He can then advance these LOP's to the time of taking the CD bearing to plot a running fix.

Enter the table with the difference between the course and first bearing (angle BAD in Figure 822) along the top of the table and the difference between the course and second bearing (angle CBD) at the left of the table. For each pair of angles listed, two numbers are given. To find the distance from the landmark at the time of the second bearing (BD), multiply the distance run between bearings (in nautical miles) by the first number from Table 18. To find the distance when the object is abeam (CD), multiply the distance run between A and B by the second number from the table. If the run between bearings is exactly 1 mile, the tabulated values are the distances sought.

Example: *A ship is steaming on course 050°, speed 15 knots. At 1130 a lighthouse bears 024°, and at 1140 it bears 359°.*

Required:

(1) *Distance from the light at 1140.*

(2) *Distance form the light when it is broad on the port beam.*

Solution:

(1) *The difference between the course and the first bearing (050° – 24°) is 26°, and the difference between the course and the second bearing (050° + 360° - 359°) is 51°.*

(2) *From the table 18, the two numbers (factors are 1.04 and 0.81, found by interpolation.*

(3) *The distance run between bearings is 2.5 miles (10 minutes at 15 knots).*

(4) T*he distance from the lighthouse at the time of the second bearing is 2.5 × 1.04 = 2.6 miles.*

(5) *The distance from the lighthouse when it is broad on the beam is 2.5 × 0.81 = 2.0 miles.*

Answer: *(1) D 2.6 mi., (2) D 2.0 mi.*

This method yields accurate results only if the helmsman has steered a steady course and the navigator uses the vessel's speed over ground.

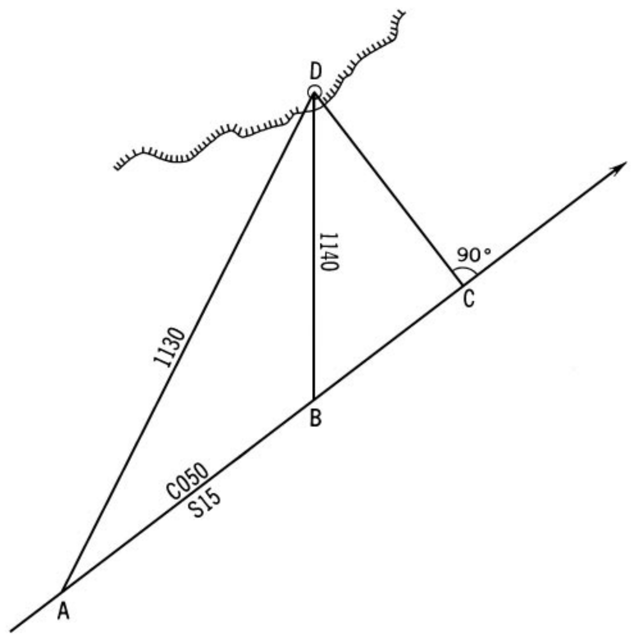


Figure 822. Triangles involved in a Table 18 running fix.

MINIMIZING ERRORS IN PILOTING

823. Common Errors

Piloting requires a thorough familiarity with principles involved, constant alertness, and judgment. A study of groundings reveals that the cause of most is a failure to use or interpret available information. Among the more common errors are:

1. Failure to obtain or evaluate soundings.
2. Mis-identification of aids to navigation.
3. Failure to use available navigational aids effectively.
4. Failure to correct charts.
5. Failure to adjust a magnetic compass or keep a table of corrections.
6. Failure to apply deviation.
7. Failure to apply variation.
8. Failure to check gyro and magnetic compass readings regularly.
9. Failure to keep a dead reckoning plot.
10. Failure to plot new information.
11. Failure to properly evaluate information.
12. Poor judgment.
13. Failure to use information in charts and navigation publications.
14. Poor navigation team organization.
15. Failure to "keep ahead of the vessel."
16. Failure to have backup navigation methods in place.

Some of the errors listed above are mechanical and some are matters of judgment. Conscientiously applying the principles and procedures of this chapter will go a long way towards eliminating many of the mechanical errors. However, the navigator must guard against the feeling that in following a checklist he has eliminated all sources of error. A navigator's judgment is just as important as his checklists.

824. Minimizing Errors With A Two Bearing Plot

When measuring bearings from two NAVAIDS, the fix error resulting from an error held constant for both observations is minimized if the angle of intersection of the bearings is 90°.

If the observer in Figure 824a is located at point T and the bearings of a beacon and cupola are observed and plotted without error, the intersection of the bearing lines lies on the circumference of a circle passing through the beacon, cupola, and the observer. With constant error, the angular difference of the bearings of the beacon and the cupola is not affected. Thus, the angle formed at point F by the bearing lines plotted with constant error is equal to the angle formed at point T by the bearing lines plotted without error. From geometry it is known that angles having their apexes on the circumference of a circle and that are subtended by the same chord are equal. Since the angles at points T and F are equal and the angles are subtended by the same chord, the intersection at point F lies on the circumference of a circle passing through the beacon, cupola, and the observer.

Assuming only constant error in the plot, the direction of displacement of the two-bearing fix from the position of the observer is in accordance with the sign (or direction) of the constant error. However, a third bearing is required to determine the direction of the constant error.

Assuming only constant error in the plot, the two-bearing fix lies on the circumference of the circle passing through the two charted objects observed and the observer. The fix error, the length of the chord FT in Figure 824b, depends on the magnitude of the constant error $\in$, the distance between the charted objects, and the cosecant of the angle of cut, angle θ. In Figure 824b,

$$\text{The fix error} = FT = \frac{\varepsilon BC \csc\theta}{2}$$

where ε is the magnitude of the constant error, BC is the length of the chord BC, and θ is the angle of the LOP's intersection.

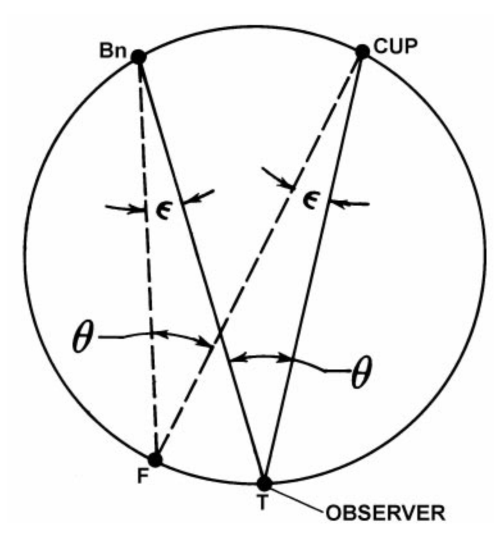


Figure 824a. Two-bearing plot.

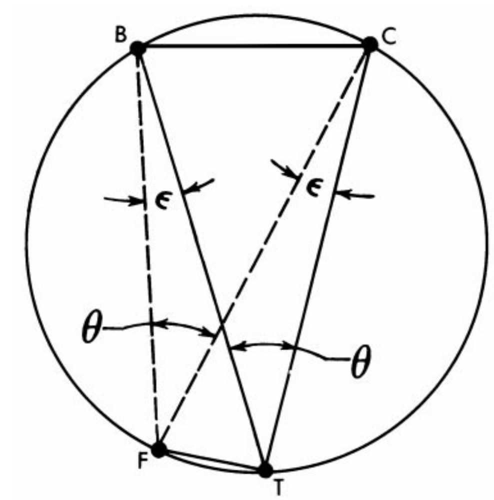


Figure 824b. Two-bearing plot with constant error.

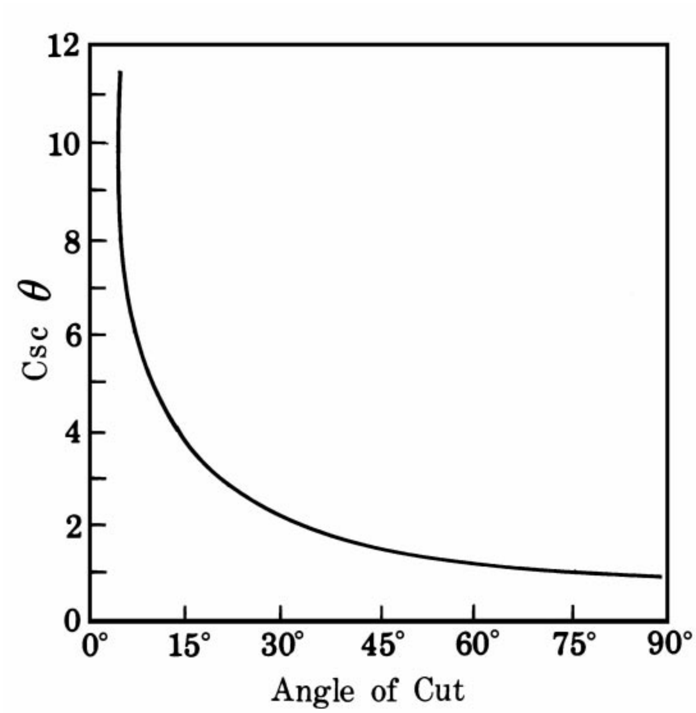


Figure 824c. Error of two-bearing plot.

Since the fix error is a function of the cosecant of the angle of intersection, it is least when the angle of intersection is 90°. As illustrated in Figure 824c, the error increases in accordance with the cosecant function as the angle of intersection decreases. The increase in the error becomes quite rapid after the angle of intersection has decreased to below about 30°. With an angle of intersection of 30°, the fix error is about twice that at 90°.

825. Adjusting A Fix For Constant Error By The Trial And Error Technique

If several fixes obtained by bearings on three objects produce triangles of error of about the same size, suspect a constant error in observing or plotting the bearings. If applying of a constant error to all bearings results in a point, or near-point, fix, apply such a correction to all subsequent fixes. Figure 825 illustrates this technique. The solid lines indicate the original plot, and the broken lines indicate each line of position moved 3° in a clockwise direction.

Employ this procedure carefully. Attempt to find and eliminate the error source. The error may be in the gyrocompass, the repeater, or the bearing transmission system. Compare the resulting fix positions with a satellite position, a radar position, or the charted sounding. A high degree of correlation between these three independent positioning systems and an "adjusted" visual fix is further confirmation of a constant bearing error.

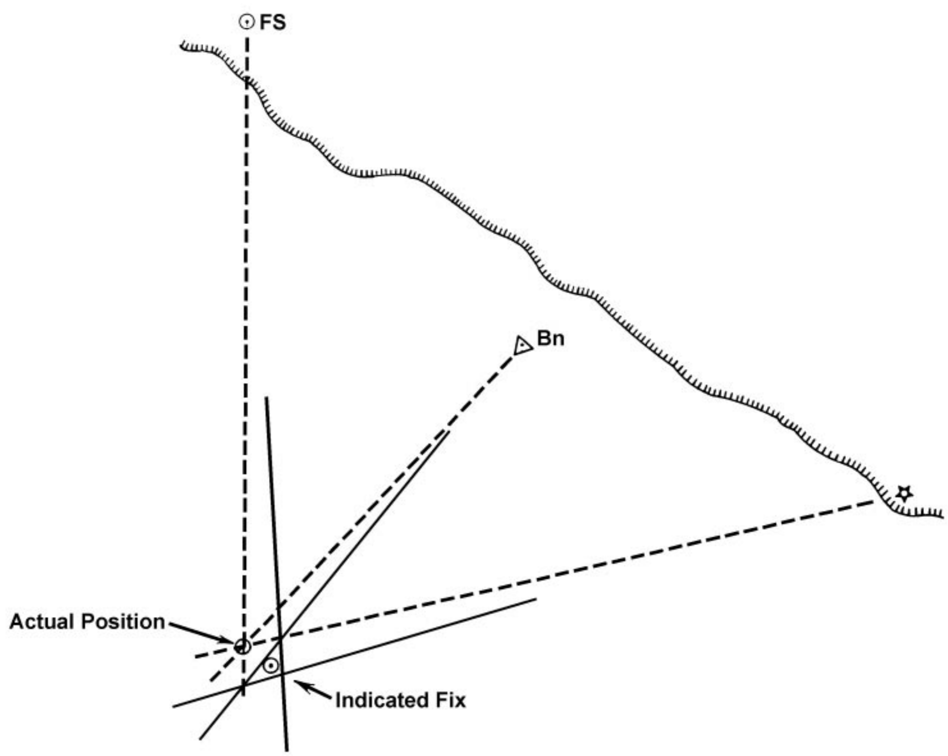


Figure 825. Adjusting a fix for constant error.

TRAINING

826. Piloting Simulators

Civilian piloting training has traditionally been a function of both maritime academies and on-the-job experience. The latter is usually more valuable, because there is no substitute for experience in developing judgment. Military piloting training consists of advanced correspondence courses and formal classroom instruction combined with duties on the bridge. U.S. Navy Quartermasters frequently attend Ship's Piloting and Navigation (SPAN) trainers as a routine segment of shoreside training. Military vessels in general have a much clearer definition of responsibilities, as well as more people to carry them out, than civilian ships.

Computer technology has made possible the develop-

ment of computerized **ship simulators**, which allow piloting experience to be gained without risking accidents at sea and without incurring underway expense. Simulators range from simple micro-computer-based software to a completely equipped ship's bridge with radar, engine controls, 360° horizon views, programmable sea motions, and the capability to simulate almost any navigational situation.

A different type of simulator consists of scale models of ships in a pond. The models, actually small craft of about 20-30 feet, have hull forms and power-to-weight ratios similar to various types of ships, primarily supertankers, and the operator pilots the vessel from a position such that his view is from the craft's "bridge." These are primarily used in training pilots and masters in docking maneuvers with exceptionally large vessels.

The first computer ship simulators came into use in the late 1970s. Several years later the U.S. Coast Guard began accepting a limited amount of simulator time as "sea time" for licensing purposes. The most sophisticated simulators have a full 360° horizon, visible from a completely equipped wheelhouse, which can be programmed for movement, noise, and vibration. They can simulate virtually any conditions encountered at sea or in piloting waters, including land, aids to navigation ice, wind, fog, snow, rain, and lightning. The system can also be programmed to simulate hydrodynamic effects such as shallow water, passing vessels, current, and tugs.

Virtually any type of vessel can be simulated, including tankers, bulkers, container ships, tugs and barges, yachts, and military vessels. Similarly, any given navigational situation can be modeled, including passage through any chosen harbor, river, or passage, convoy operations, meeting and passing situations at sea and in harbors.

Simulators are used not only to train mariners, but also to test feasibility of port and harbor plans and visual aids to navigation system designs. This allows pilots to "navigate" simulated ships through simulated harbors before construction begins to test the adequacy of channels, turning basins, aids to navigation, and other factors.

A full-capability simulator consists of a ship's bridge which may have motion and noise/vibration inputs, a programmable visual display system which projects a simulated picture of the area surrounding the vessel in both daylight and night modes, image generators for the various inputs to the scenario such as video images and radar, a central data processor, a human factors monitoring system which may record and videotape bridge activities for later analysis, and a control station where instructors control the entire scenario.

Some simulators are part-task in nature, providing specific training in only one aspect of navigation such as radar navigation, collision avoidance, or night navigation.

CHAPTER 9

TIDES AND TIDAL CURRENTS

ORIGINS OF TIDES

900. Introduction

Tides are the periodic motion of the waters of the sea due to changes in the attractive forces of the moon and sun upon the rotating earth. Tides can either help or hinder a mariner. A high tide may provide enough depth to clear a bar, while a low tide may prevent entering or leaving a harbor. Tidal current may help progress or hinder it, may set the ship toward dangers or away from them. By understanding tides, and by making intelligent use of predictions published in tide and tidal current tables and of descriptions in sailing directions, the navigator can plan an expeditious and safe passage.

901. Tide And Current

The rise and fall of tide is accompanied by horizontal movement of the water called **tidal current**. It is necessary to distinguish clearly between tide and tidal current, for the relation between them is complex and variable. For the sake of clarity mariners have adopted the following definitions: Tide is the *vertical* rise and fall of the water, and tidal current is the *horizontal* flow. The tide rises and falls, the tidal current floods and ebbs. The navigator is concerned with the *amount* and *time* of the tide, as it affects access to shallow ports. The navigator is concerned with the time, speed, and direction of the tidal current, as it will affect his ship's position, speed, and course.

Tides are superimposed on nontidal rising and falling water levels, caused by weather, seismic events, or other natural forces. Similarly, tidal currents are superimposed upon non-tidal currents such as normal river flows, floods, freshets, etc.

902. Causes Of Tides

The principal tidal forces are generated by the moon and sun. The moon is the main tide-generating body. Due to its greater distance, the sun's effect is only 46 percent of the moon's. Observed tides will differ considerably from the tides predicted by equilibrium theory since size, depth, and configuration of the basin or waterway, friction, land masses, inertia of water masses, Coriolis acceleration, and other factors are neglected in this theory. Nevertheless, equilibrium theory is sufficient to describe the magnitude and distribution of the main tide-generating forces across the surface of the earth.

Newton's universal law of gravitation governs both the orbits of celestial bodies and the tide-generating forces which occur on them. The force of gravitational attraction between any two masses, m_1 and m_2, is given by:

$$F = \frac{Gm_1m_2}{d^2}$$

where d is the distance between the two masses, and G is a constant which depends upon the units employed. This law assumes that m_1 and m_2 are point masses. Newton was able to show that homogeneous spheres could be treated as point masses when determining their orbits.

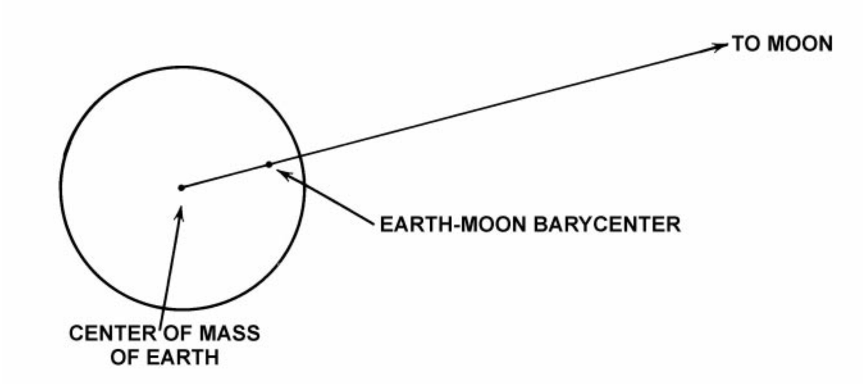


Figure 902a. Earth-moon barycenter.

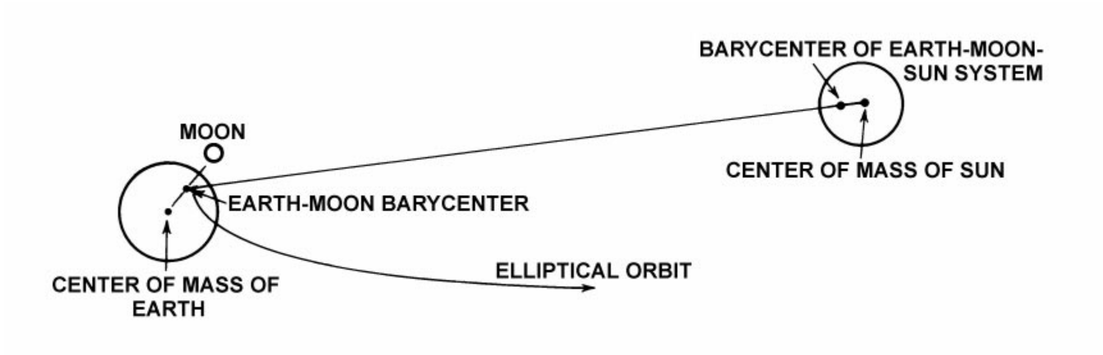


Figure 902b. Orbit of earth-moon barycenter (not to scale).

However, when computing differential gravitational forces, the actual dimensions of the masses must be taken into account.

Using the law of gravitation, it is found that the orbits of two point masses are conic sections about the **barycenter** of the two masses. If either one or both of the masses are homogeneous spheres instead of point masses, the orbits are the same as the orbits which would result if all of the mass of the sphere were concentrated at a point at the center of the sphere. In the case of the earth-moon system, both the earth and the moon describe elliptical orbits about their barycenter if both bodies are assumed to be homogeneous spheres and the gravitational forces of the sun and other planets are neglected. The earth-moon barycenter is located 74/100 of the distance from the center of the earth to its surface, along the line connecting the earth's and moon's centers.

Thus the center of mass of the earth describes a very small ellipse about the earth-moon barycenter, while the center of mass of the moon describes a much larger ellipse about the same barycenter. If the gravitational forces of the other bodies of the solar system are neglected, Newton's law of gravitation also predicts that the earth-moon barycenter will describe an orbit which is approximately elliptical about the barycenter of the sun-earth-moon system. This barycentric point lies inside the sun.

903. The Earth-Moon-Sun System

The fundamental tide-generating force on the earth has two interactive but distinct components. The tide-generating forces are differential forces between the gravitational attraction of the bodies (earth-sun and earth-moon) and the centrifugal forces on the earth produced by the earth's orbit around the sun and the moon's orbit around the earth. Newton's Law of Gravitation and his Second Law of Motion can be combined to develop formulations for the differential force at any point on the earth, as the direction and magnitude are dependent on where you are on the earth's surface. As a result of these differential forces, the tide generating forces F_{dm} (moon) and F_{ds} (sun) are inversely proportional to the cube of the distance between the bodies, where:

$$F_{dm} = \frac{GM_mR_e}{d_m{}^3}; \quad F_{ds} = \frac{GM_sR_e}{d_s{}^3}$$

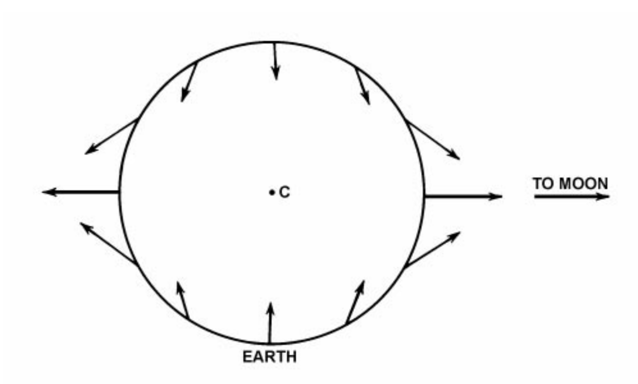


Figure 903a. Differential forces along a great circle connecting the sublunar point and antipode.

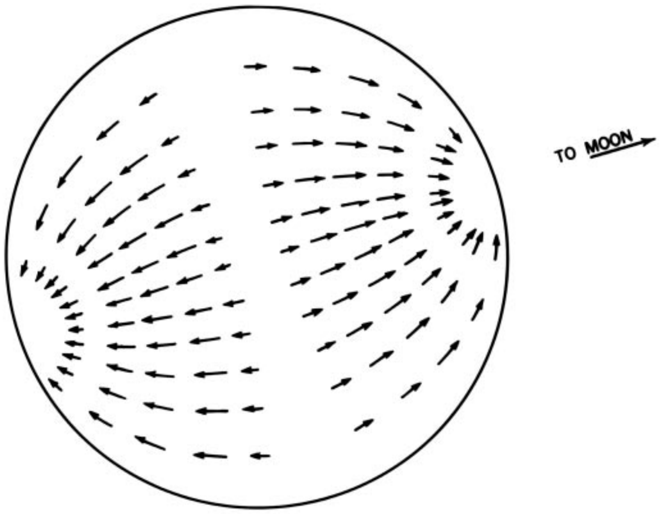


Figure 903b. Tractive forces across the surface of the earth.

where M_m is the mass of the moon and M_s is the mass of the sun, R_e is the radius of the earth and d is the distance to the moon or sun. This explains why the tide-generating force of the sun is only 46/100 of the tide-generating force of the moon. Even though the sun is much more massive, it is also much farther away.

Using Newton's second law of motion, we can calculate the differential forces generated by the moon and the sun affecting any point on the earth. The easiest calculation is for the point directly below the moon, known as the **sublunar point**, and the point on the earth exactly opposite, known as the **antipode**. Similar calculations are done for the sun.

If we assume that the entire surface of the earth is covered with a uniform layer of water, the differential forces may be resolved into vectors perpendicular and parallel to the surface of the earth to determine their effect.

The perpendicular components change the mass on which they are acting, but do not contribute to the tidal effect. The horizontal components, parallel to the earth's surface, have the effect of moving the water in a horizontal direction toward the sublunar and antipodal points until an equilibrium position is found. The *horizontal* components of the differential forces are the principal tide-generating forces. These are also called **tractive** forces. Tractive forces are zero at the sublunar and antipodal points and along the great circle halfway between these two points. Tractive forces are maximum along the small circles located 45° from the sublunar point and the antipode. Figure 903b shows the tractive forces across the surface of the earth.

Equilibrium will be reached when a bulge of water has formed at the sublunar and antipodal points such that the tractive forces due to the moon's differential gravitational forces on the mass of water covering the surface of the earth are just balanced by the earth's gravitational attraction (Figure 903c).

Now consider the effect of the rotation of the earth. If the declination of the moon is 0°, the bulges will lie on the equator. As the earth rotates, an observer at the equator will note that the moon transits approximately every 24 hours and 50 minutes. Since there are two bulges of water on the equator, one at the sublunar point and the other at the antipode, the observer will also see two high tides during this interval with one high tide occurring when the moon is overhead and another high tide 12 hours 25 minutes later when the observer is at the antipode. He will also experience a low tide between each high tide. The theoretical range of these equilibrium tides at the equator will be less than 1 meter.

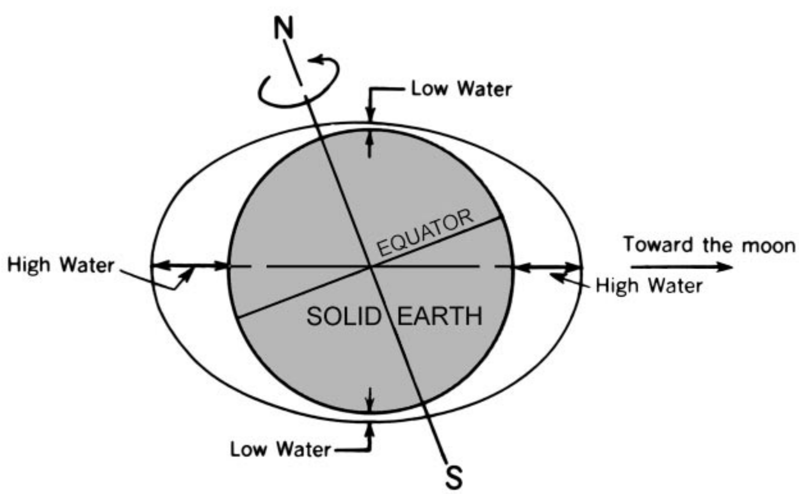


Figure 903c. Theoretical equilibrium configuration due to moon's differential gravitational forces. One bulge of the water envelope is located at the sublunar point, the other bulge at the antipode.

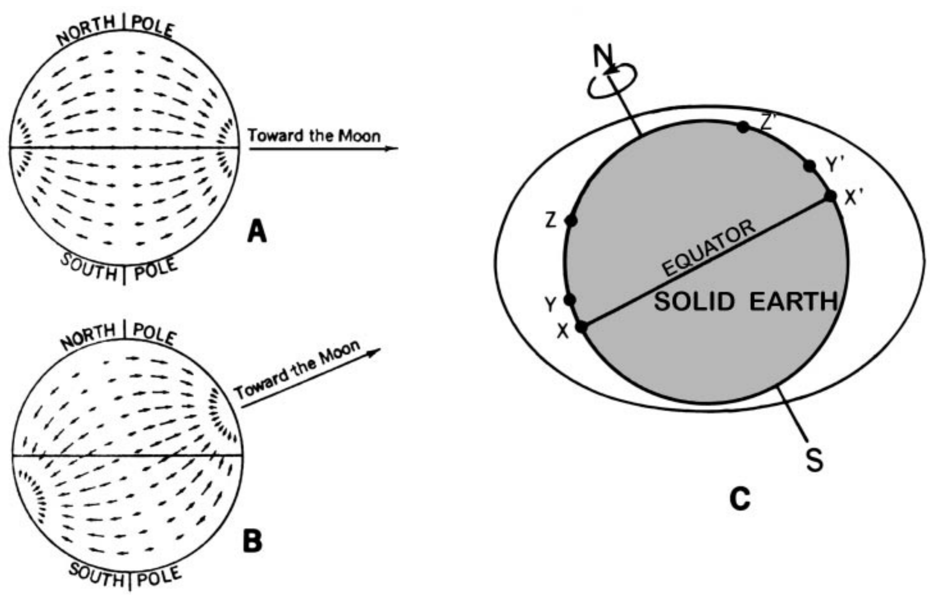


Figure 903d. Effects of the declination of the moon.

The heights of the two high tides should be equal at the equator. At points north or south of the equator, an observer would still experience two high and two low tides, but the heights of the high tides would not be as great as they are at the equator. The effects of the declination of the moon are shown in Figure 903d, for three cases, A, B, and C.

A. When the moon is on the plane of the equator, the forces are equal in magnitude at the two points on the same parallel of latitude and 180° apart in longitude.
B. When the moon has north or south declination, the forces are unequal at such points and tend to cause an inequality in the two high waters and the two low waters each day.
C. Observers at points X, Y, and Z experience one high tide when moon is on their meridian, then another high tide 12 hours 25 minutes later when at X', Y', and Z'. The second high tide is the same at X' as at X. High tides at Y' and Z' are lower than high tides at Y and Z.

The preceding discussion pertaining to the effects of the moon is equally valid when discussing the effects of the sun, taking into account that the magnitude of the solar effect is smaller. Hence, the tides will also vary according to the sun’s declination and its varying distance from the earth. A second envelope of water representing the equilibrium tides due to the sun would resemble the envelope shown in Figure 903c except that the heights of the high tides would be smaller, and the low tides correspondingly not as low.

FEATURES OF TIDES

904. General Features

At most places the tidal change occurs twice daily. The tide rises until it reaches a maximum height, called **high tide** or **high water**, and then falls to a minimum level called **low tide** or **low water**.

The *rate* of rise and fall is not uniform. From low water, the tide begins to rise slowly at first, but at an increasing rate until it is about halfway to high water. The rate of rise then decreases until high water is reached, and the rise ceases. The falling tide behaves in a similar manner. The period at high or low water during which there is no apparent change of level is called **stand**. The difference in height between consecutive high and low waters is the **range**.

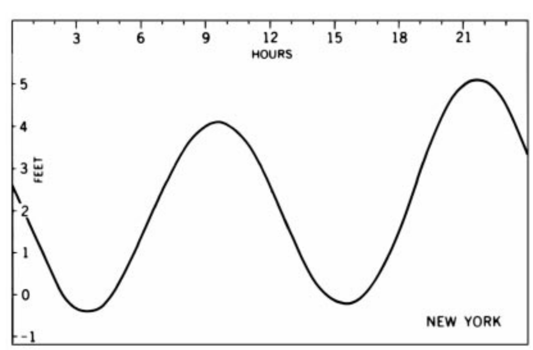


Figure 904. The rise and fall of the tide at New York, shown graphically.

Figure 904 is a graphical representation of the rise and fall of the tide at New York during a 24-hour period. The curve has the general form of a variable sine curve.

905. Types Of Tide

A body of water has a natural period of oscillation, dependent upon its dimensions. None of the oceans is a single oscillating body; rather each one is made up of several separate oscillating basins. As such basins are acted upon by the tide-producing forces, some respond more readily to daily or diurnal forces, others to semidiurnal forces, and others almost equally to both. Hence, tides are classified as one of three types, semidiurnal, diurnal, or mixed, according to the characteristics of the tidal pattern.

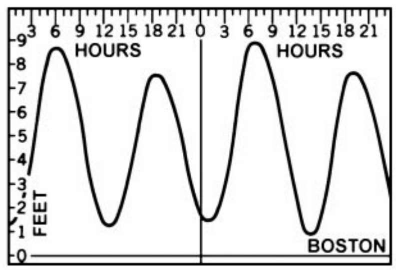


Figure 905a. Semidiurnal type of tide.

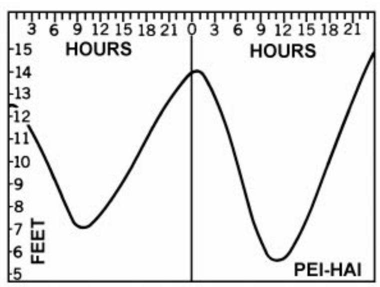


Figure 905b. Diurnal tide.

In the **semidiurnal tide**, there are two high and two low waters each tidal day, with relatively small differences in the respective highs and lows. Tides on the Atlantic coast of the United States are of the semidiurnal type, which is illustrated in Figure 905a by the tide curve for Boston Harbor.

In the **diurnal tide**, only a single high and single low water occur each tidal day. Tides of the diurnal type occur along the northern shore of the Gulf of Mexico, in the Java Sea, the Gulf of Tonkin, and in a few other localities. The tide curve for Pei-Hai, China, illustrated in Figure 905b, is an example of the diurnal type.

In the **mixed tide**, the diurnal and semidiurnal oscillations are both important factors and the tide is characterized by a large inequality in the high water heights, low water heights, or in both. There are usually two high and two low waters each day, but occasionally the tide may become diurnal. Such tides are prevalent along the Pacific coast of the United States and in many other parts of the world. Examples of mixed types of tide are shown in Figure 905c. At Los Angeles, it is typical that the inequalities in the high and low waters are about the same. At Seattle the greater inequalities are typically in the low waters, while at Honolulu it is the high waters that have the greater inequalities.

906. Solar Tide

The natural period of oscillation of a body of water may accentuate either the solar or the lunar tidal oscilla-

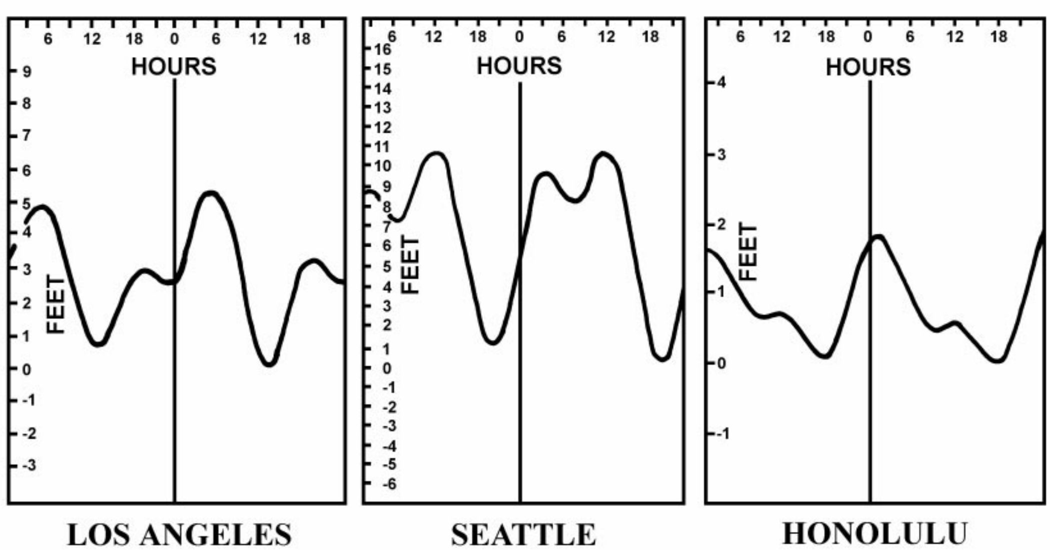


Figure 905c. Mixed tide.

tions. Though as a general rule the tides follow the moon, the relative importance of the solar effect varies in different areas. There are a few places, primarily in the South Pacific and the Indonesian areas, where the solar oscillation is the more important, and at those places the high and low waters occur at about the same time each day. At Port Adelaide, Australia the solar and lunar semidiurnal oscillations are equal and nullify one another at neaps.

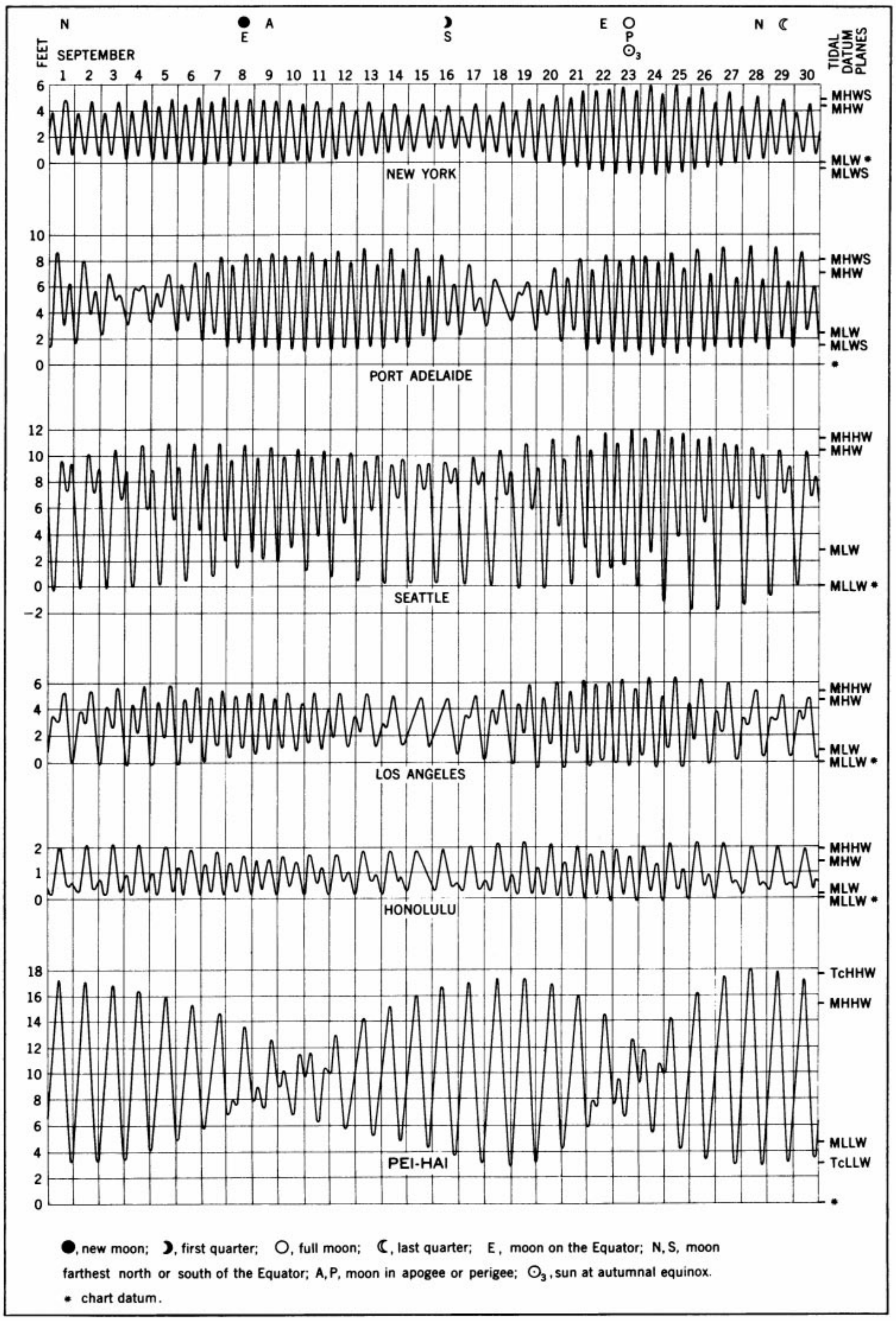


Figure 908a. Monthly tidal variations at various places.

907. Special Tidal Effects

As a wave enters shallow water, its speed is decreased. Since the trough is shallower than the crest, it is retarded more, resulting in a steepening of the wave front. In a few estuaries, the advance of the low water trough is so much retarded that the crest of the rising tide overtakes the low, and advances upstream as a breaking wave called a **bore**. Bores that are large and dangerous at times of large tidal ranges may be mere ripples at those times of the month when the range is small. Examples occur in the Petitcodiac River in the Bay of Fundy, and at Haining, China, in the Tsientang Kaing. The tide tables indicate where bores occur.

Other special features are the **double low water** (as at Hoek Van Holland) and the **double high water** (as at Southampton, England). At such places there is often a slight fall or rise in the middle of the high or low water period. The practical effect is to create a longer period of stand at high or low tide. The tide tables list these and other peculiarities where they occur.

908. Variations In Range

Though the tide at a particular place can be classified as to type, it exhibits many variations during the month (Figure 908a). The range of the tide varies according to the intensity of the tide-producing forces, though there may be a lag of a day or two between a particular astronomic cause and the tidal effect.

The combined lunar-solar effect is obtained by adding the moon's tractive forces vectorially to the sun's tractive forces. The resultant tidal bulge will be predominantly lunar with modifying solar effects upon both the height of the tide and the direction of the tidal bulge. Special cases of interest occur during the times of new and full moon (Figure 908b). With the earth, moon, and sun lying approximately on the same line, the tractive forces of the sun are acting in the same direction as the moon's tractive forces (modified by declination effects). The resultant tides are called **spring tides**, whose ranges are greater than average.

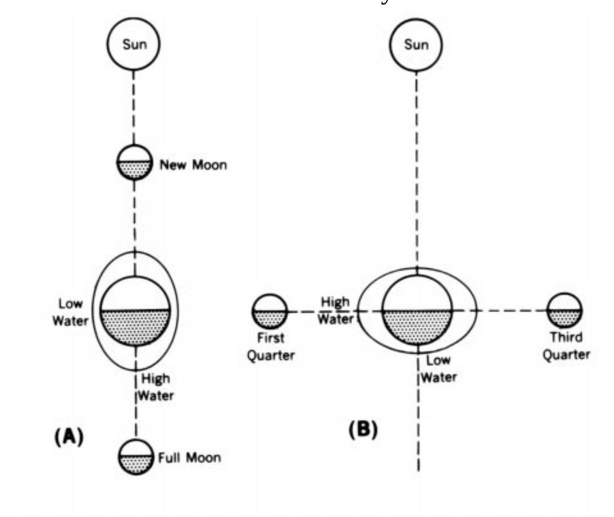


Figure 908b. (A) Spring tides occur at times of new and full moon. Range of tide is greater than average since solar and lunar tractive forces act in same direction. (B) Neap tides occur at times of first and third quarters. Range of tide is less than average since solar and lunar tractive forces act at right angles.

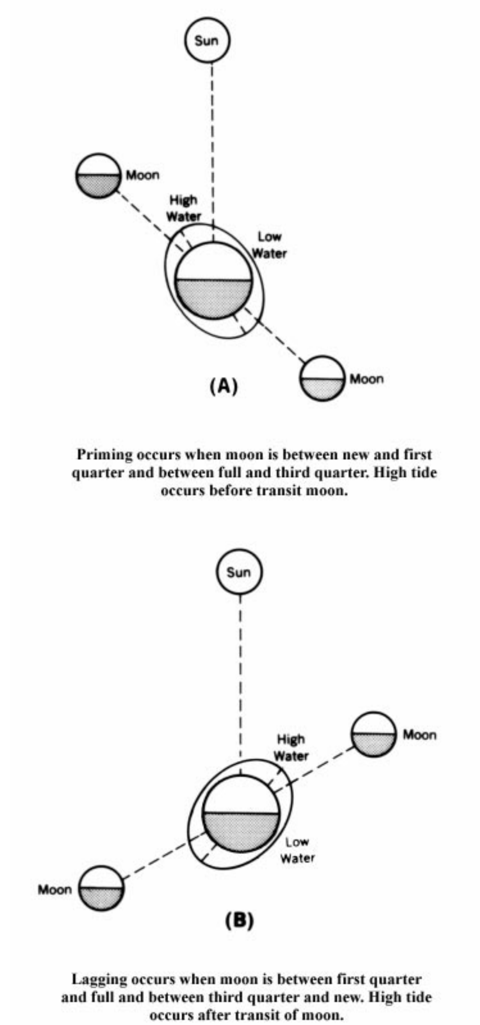


Figure 908c. Priming and lagging the tides.

Between the spring tides, the moon is at first and third quarters. At those times, the tractive forces of the sun are acting at approximately right angles to the moon's tractive forces. The results are tides called **neap tides**, whose ranges are less than average.

With the moon in positions between quadrature and new or full, the effect of the sun is to cause the tidal bulge to either lag or precede the moon (Figure 908c). These effects are called **priming** and **lagging** the tides.

Thus, when the moon is at the point in its orbit nearest the earth (at perigee), the lunar semidiurnal range is increased and **perigean tides** occur. When the moon is farthest from the earth (at apogee), the smaller **apogean tides** occur. When the moon and sun are in line and pulling together, as at new and full moon, **spring tides** occur (the term spring has nothing to do with the season of year); when the moon and sun oppose each other, as at the quadratures, the smaller **neap tides** occur. When certain of these phenomena coincide, **perigean spring tides** and **apogean neap tides** occur.

These are variations in the semidiurnal portion of the tide. Variations in the diurnal portion occur as the moon and sun change declination. When the moon is at its maximum semi-monthly declination (either north or south), **tropic tides** occur in which the diurnal effect is at a maximum. When it crosses the equator, the diurnal effect is a minimum and **equatorial tides** occur.

When the range of tide is increased, as at spring tides, there is more water available only at high tide; at low tide there is less, for the high waters rise higher and the low waters fall lower at these times. There is more water at neap low water than at spring low water. With tropic tides, there is usually more depth at one low water during the day than at the other. While it is desirable to know the meanings of these terms, the best way of determining the height of the tide at any place and time is to examine the tide predictions for the place as given in the tide tables, which take all these effects into account.

909. Tidal Cycles

Tidal oscillations go through a number of cycles. The shortest cycle, completed in about 12 hours and 25 minutes for a semidiurnal tide, extends from any phase of the tide to the next recurrence of the same phase. During a lunar day (averaging 24 hours and 50 minutes) there are two highs and two lows (two of the shorter cycles) for a semidiurnal tide. The moon revolves around the earth with respect to the sun in a **synodical month** of about 29 1/2 days, commonly called the **lunar month**. The effect of the phase variation is completed in one-half a synodical month or about 2 weeks as the moon varies from new to full or full to new. The effect of the moon's declination is also repeated in one-half of a **tropical month** of 27 1/3 days or about every 2 weeks. The cycle involving the moon's distance requires an **anomalistic month** of about 27 1/2 days. The sun's declination and distance cycles are respectively a half year and a year in length. An important lunar cycle, called the **nodal period**, is 18.6 years (usually expressed in round figures as 19 years). For a tidal value, particularly a range, to be considered a true mean, it must be either based upon observations extended over this period of time, or adjusted to take account of variations known to occur during the nodal period.

910. Time Of Tide

Since the lunar tide-producing force has the greatest effect in producing tides at most places, the tides "follow the moon." Because the earth rotates, high water lags behind both upper and lower meridian passage of the moon. The **tidal day**, which is also the lunar day, is the time between consecutive transits of the moon, or 24 hours and 50 minutes on the average. Where the tide is largely semidiurnal in type, the **lunitidal interval** (the interval between the moon's meridian transit and a particular phase of tide) is fairly constant throughout the month, varying somewhat with the tidal cycles. There are many places, however, where solar or diurnal oscillations are effective in upsetting this relationship. The interval generally given is the average elapsed time from the meridian transit (upper or lower) of the moon until the next high tide. This may be called **mean high water lunitidal interval** or **corrected** (or **mean**) **establishment**. The **common establishment** is the average interval on days of full or new moon, and approximates the mean high water lunitidal interval.

In the ocean, the tide may be in the nature of a progressive wave with the crest moving forward, a stationary or standing wave which oscillates in a seesaw fashion, or a combination of the two. Consequently, caution should be used in inferring the time of tide at a place from tidal data for nearby places. In a river or estuary, the tide enters from the sea and is usually sent upstream as a progressive wave so that the tide occurs progressively later at various places upstream.

TIDAL DATUMS

911. Low Water Datums

A tidal datum is a level from which tides are measured. There are a number of such levels of reference that are important to the mariner. See Figure 911.

The most important level of reference to the mariner is the **sounding datum** shown on charts. Since the tide rises and falls continually while soundings are being taken during a hydrographic survey, the tide is recorded during the survey so that soundings taken at all stages of the tide can be reduced to a common sounding datum. Soundings on charts show depths below a selected low water datum (occasionally mean sea level), and tide predictions in tide tables show heights above and below the same level. The depth of water available at any time

is obtained by adding algebraically the height of the tide at the time in question to the charted depth.

By international agreement, the level used as chart datum should be low enough so that low waters do not fall very far below it. At most places, the level used is one determined from a mean of a number of low waters (usually over a 19 year period); therefore, some low waters can be expected to fall below it. The following are some of the datums in general use.

Mean low water (MLW) is the average height of all low waters at a given place. About half of the low waters fall below it, and half above.

Mean low water springs (MLWS), usually shortened to low water springs, is the average level of the low waters that occur at the times of spring tides.

Mean lower low water (MLLW) is the average height of the lower low waters of each tidal day.

Tropic lower low water (TcLLW) is the average height of the lower low waters (or of the single daily low waters if the tide becomes diurnal) that occur when the moon is near maximum declination and the diurnal effect is most pronounced. This datum is not in common use as a tidal reference.

Indian spring low water (ISLW), sometimes called **Indian tide plane** or **harmonic tide plane**, is a low water datum that includes the spring effect of the semi-diurnal portion of the tide and the tropic effect of the diurnal portion. It is about the level of lower low water of mixed tides at the time that the moon's maximum declination coincides with the time of new or full moon.

Mean lower low water springs (MLLWS) is the average level of the lower of the two low waters on the days of spring tides.

Some still lower datums used on charts are determined from tide observations and some are determined arbitrarily and later referred to the tide. Most of them fall close to one or the other of the following two datums.

Lowest normal low water is a datum that approximates the average height of monthly lowest low waters, discarding any tides disturbed by storms.

Lowest low water is an extremely low datum. It conforms generally to the lowest tide observed, or even

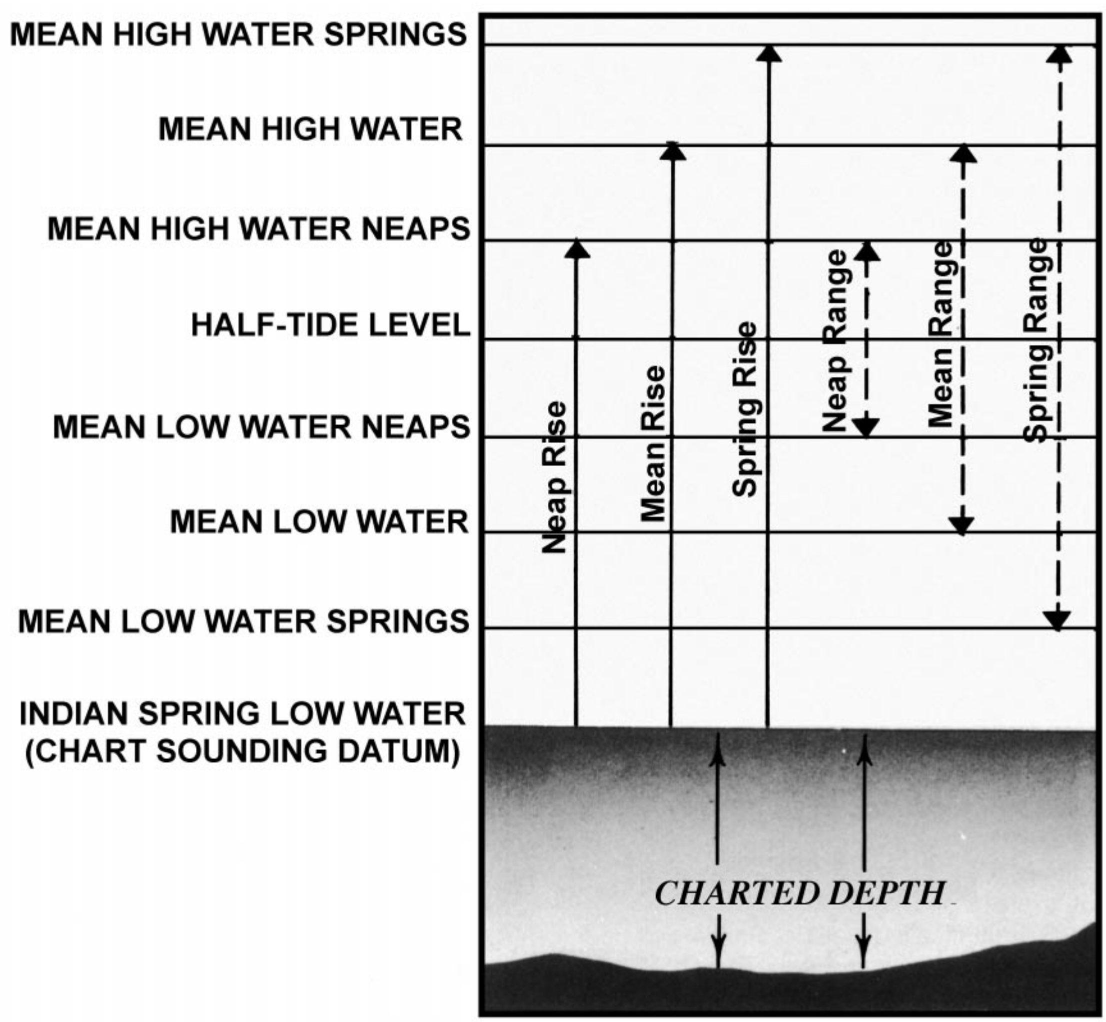


Figure 911. Variations in the ranges and heights of tide where the chart sounding datum is Indian Spring Low Water.

somewhat lower. Once a tidal datum is established, it is sometimes retained for an indefinite period, even though it might differ slightly from a better determination from later observations. When this occurs, the established datum may be called **low water datum**, **lower low water datum**, etc. These datums are used in a limited area and primarily for river and harbor engineering purposes. Examples are Boston Harbor Low Water Datum and Columbia River Lower Low Water Datum.

Figure 911 illustrates variations in the ranges and heights of tides in a locality such as the Indian Ocean, where predicted and observed water levels are referenced to a chart sounding datum that will always cause them to be additive relative to the charted depth.

In some areas where there is little or no tide, such as the Baltic Sea, **mean sea level (MSL)** is used as chart datum. This is the average height of the surface of the sea for all stages of the tide over a 19 year period. This may differ slightly from half-tide level, which is the level midway between mean high water and mean low water.

Inconsistencies of terminology are found among charts of different countries and between charts issued at different times.

Large-scale charts usually specify the datum of soundings and may contain a tide note giving mean heights of the tide at one or more places on the chart. These heights are intended merely as a rough guide to the change in depth to be expected under the specified conditions. They should not be used for the prediction of heights on any particular day, which should be obtained from tide tables.

912. High Water Datums

Heights of terrestrial features are usually referred on nautical charts to a high water datum. This gives the mariner a margin of error when passing under bridges, overhead cables, and other obstructions. The one used on charts of the United States, its territories and possessions, and widely used elsewhere, is **mean high water (MHW)**, which is the average height of all high waters over a 19 year period. Any other high water datum in use on charts is likely to be higher than this. Other high water datums are **mean high water springs (MHWS)**, which is the average level of the high waters that occur at the time of spring tides; **mean higher high water (MHHW)**, which is the average height of the higher high waters of each tidal day; and **tropic higher high water (TcHHW)**, which is the average height of the higher high waters (or the single daily high waters if the tide becomes diurnal) that occur when the moon is near maximum declination and the diurnal effect is most pronounced. A reference merely to “high water” leaves some doubt as to the specific level referred to, for the height of high water varies from day to day. Where the range is large, the variation during a 2 week period may be considerable.

Because there are periodic and apparent secular trends in sea level, a specific 19 year cycle (the **National Tidal Datum Epoch**) is issued for all United States datums. The National Tidal Datum Epoch officially adopted by the National Ocean Service is presently 1960 through 1978. The Epoch is periodically reviewed for revision.

TIDAL CURRENTS

913. Tidal And Nontidal Currents

Horizontal movement of water is called **current**. It may be either “tidal” and “nontidal.” **Tidal current** is the periodic horizontal flow of water accompanying the rise and fall of the tide. **Nontidal current** includes all currents not due to the tidal movement. Nontidal currents include the permanent currents in the general circulatory system of the oceans as well as temporary currents arising from meteorological conditions. The current experienced at any time is usually a combination of tidal and nontidal currents.

914. General Features

Offshore, where the direction of flow is not restricted by any barriers, the tidal current is rotary; that is, it flows continuously, with the direction changing through all points of the compass during the tidal period. This rotation is caused by the earth’s rotation, and unless modified by local conditions, is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The speed usually varies throughout the tidal cycle, passing through two maximums in approximately opposite directions, and two minimums about halfway between the maximums in time and direction. Rotary currents can be depicted as in Figure 914a, by a series of arrows representing the direction and speed of the current at each hour. This is sometimes called a **current rose**. Because of the elliptical pattern formed by the ends of the arrows, it is also referred to as a **current ellipse**.

In rivers or straits, or where the direction of flow is more or less restricted to certain channels, the tidal current is reversing; that is, it flows alternately in approximately opposite directions with an instant or short period of little or no current, called **slack water**, at each reversal of the current. During the flow in each direction, the speed varies from zero at the time of slack water to a maximum, called strength of flood or ebb, about midway between the slacks. Reversing currents can be indicated graphically, as in Figure 914b, by arrows that represent the speed of the current at each hour. The flood is usually depicted above the slack waterline and the ebb below it. The tidal current curve formed by the ends of the arrows has the same characteristic sine form as the tide curve. In illustrations and for certain other purposes it is convenient to omit the arrows and show only the curve.

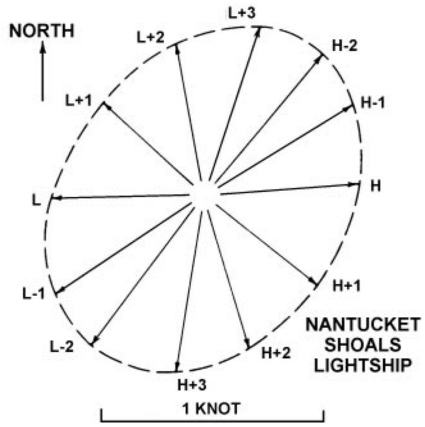


Figure 914a. Rotary tidal current. Times are hours before and after high and low tide at Nantucket Shoals. The bearing and length of each arrow represents the hourly direction and speed of the current.

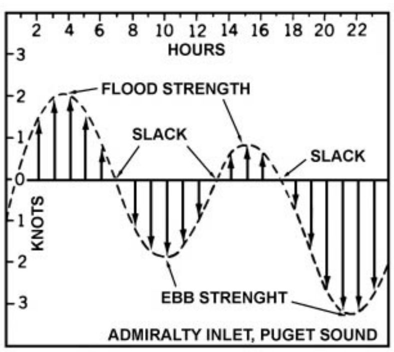


Figure 914b. Reversing tidal current.

A slight departure from the sine form is exhibited by the reversing current in a strait, such as East River, New York, that connects two tidal basins. The tides at the two ends of a strait are seldom in phase or equal in range, and the current, called **hydraulic current**, is generated largely by the continuously changing difference in height of water at the two ends. The speed of a hydraulic current varies nearly as the square root of the difference in height. The speed reaches a maximum more quickly and remains at strength for a longer period than shown in Figure 914b, and the period of weak current near the time of slack is considerably shortened.

The current direction, or **set**, is the direction *toward which* the current flows. The speed is sometimes called the **drift**. The term "velocity" is often used as the equivalent of "speed" when referring to current, although strictly speaking "velocity" implies direction as well as speed. The term "strength" is also used to refer to speed, but more often to greatest speed between consecutive slack waters. The movement toward shore or upstream is the **flood**, the movement away from shore or downstream is the **ebb**. In a purely semidiurnal current unaffected by nontidal flow, the flood and ebb each last about 6 hours and 13 minutes. But if there is either diurnal inequality or nontidal flow, the durations of flood and ebb may be quite unequal.

915. Types Of Tidal Current

Tidal currents, like tides, may be of the **semidiurnal**, **diurnal**, or **mixed** type, corresponding to a considerable degree to the type of tide at the place, but often with a stronger semidiurnal tendency.

The tidal currents in tidal estuaries along the Atlantic

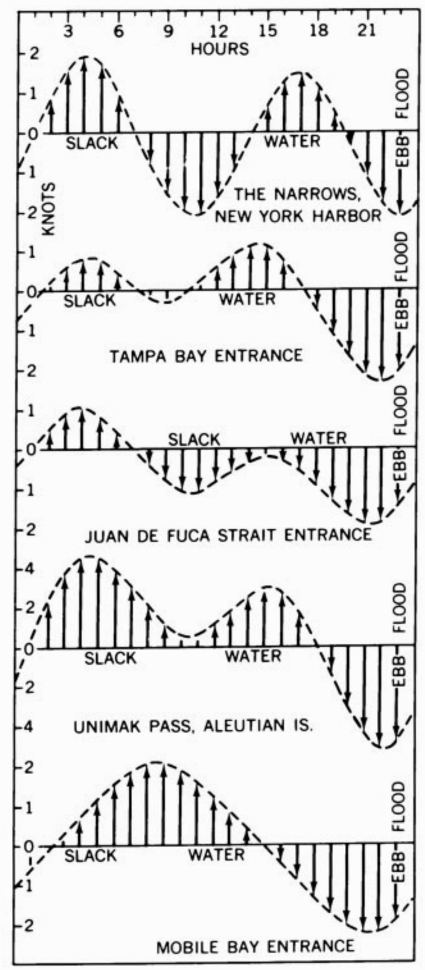


Figure 915a. Several types of reversing current. The pattern changes gradually from day to day, particularly for mixed types, passing through cycles.

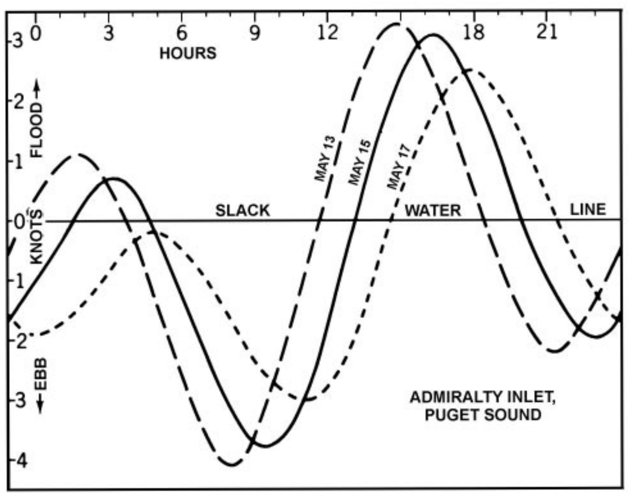


Figure 915b. Changes in a current of the mixed type. Note that each day as the inequality increases, the morning slacks draw together in time until on the 17th the morning flood disappears. On that day the current ebbs throughout the morning.

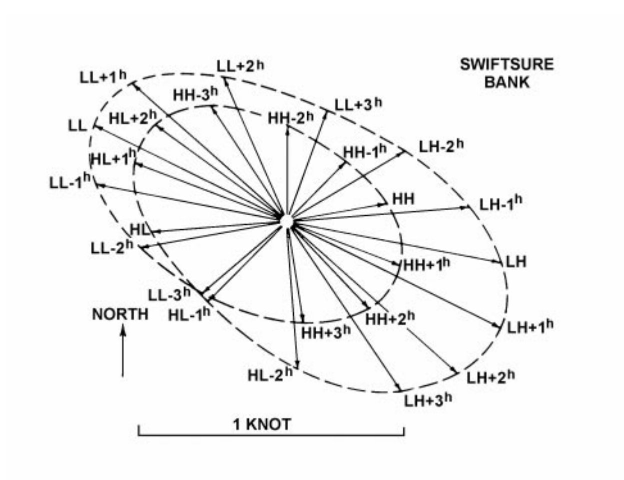


Figure 915c. Rotary tidal current with diurnal inequality. Times are in hours referred to tides (higher high, lower low, lower high, and higher low) at Swiftsure Bank.

coast of the United States are examples of the semidiurnal type of reversing current. Along the Gulf of Mexico coast, such as at Mobile Bay entrance, they are almost purely diurnal. At most places, however, the type is mixed to a greater or lesser degree. At Tampa and Galveston entrances there is only one flood and one ebb each day when the moon is near its maximum declination, and two floods and two ebbs each day when the moon is near the equator. Along the Pacific coast of the United States there are generally two floods and two ebbs every day, but one of the floods or ebbs has a greater speed and longer duration than the other, the inequality varying with the declination of the moon. The inequalities in the current often differ considerably from place to place even within limited areas, such as adjacent passages in Puget Sound and various passages between the Aleutian Islands. Figure 915a shows several types of reversing current. Figure 915b shows how the flood disappears as the diurnal inequality increases at one station.

Offshore rotary currents that are purely semidiurnal repeat the elliptical pattern each tidal cycle of 12 hours and 25 minutes. If there is considerable diurnal inequality, the plotted hourly current arrows describe a set of two ellipses of different sizes during a period of 24 hours and 50 minutes, as shown in Figure 915c, and the greater the diurnal inequality, the greater the difference between the sizes of the two ellipses. In a completely diurnal rotary current, the smaller ellipse disappears and only one ellipse is produced in 24 hours and 50 minutes.

916. Tidal Current Periods And Cycles

Tidal currents have periods and cycles similar to those of the tides, and are subject to similar variations, but flood and ebb of the current do not necessarily occur at the same times as the rise and fall of the tide.

The speed at strength increases and decreases during the 2 week period, month, and year along with the variations in the range of tide. Thus, the stronger spring and perigean currents occur near the times of new and full moon and near the times of the moon’s perigee, or at times of spring and perigean tides; the weaker neap and apogean currents occur at the times of neap and apogean tides; and tropic currents with increased diurnal speeds or with larger diurnal inequalities in speed occur at times of tropic tides; and equatorial currents with a minimum diurnal effect occur at times of equatorial tides.

As with the tide, a mean value represents an average obtained from a 19 year series. Since a series of current observations is usually limited to a few days, and seldom covers more than a month or two, it is necessary to adjust the observed values, usually by comparison with tides at a nearby place, to obtain such a mean.

917. Effect Of Nontidal Flow

The current existing at any time is seldom purely tidal, but usually includes also a nontidal current that is due to drainage, oceanic circulation, wind, or other causes. The method in which tidal and nontidal currents combine is best explained graphically, as in Figure 917a and Figure 917b. The pattern of the tidal current remains unchanged, but the curve is shifted from the point or line from which the currents are measured, in the direction of the nontidal current, and by an amount equal to it. It is sometimes more convenient graphically merely to

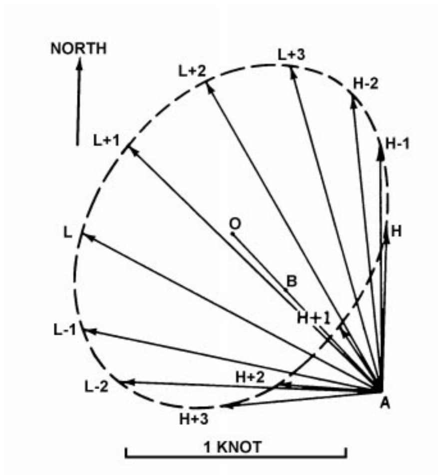


Figure 917a. Effect of nontidal current on the rotary tidal current of Figure 914a. If the the nontidal current is northwest at 0.3 knot, it may be represented by BO, and all hourly directions and speeds will then be measured from B. If it is 1.0 knot, it will be represented by AO and the actual resultant hourly directions and speeds will be measured from A, as shown by the arrows.

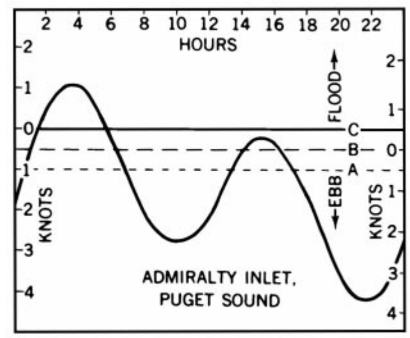


Figure 917b. Effect of nontidal current on the reversing tidal current of Figure 914b. If the nontidal current is 0.5 knot in the ebb direction, the ebb is increased by moving the slack water line from position A up 0.5 knot to position B. Speeds will then be measured from this broken line as shown by the scale on the right, and times of slack are changed. If the nontidal current is 1.0 knot in the ebb direction, as shown by line C, the speeds are as shown on the left, and the current will not reverse to a flood in the afternoon; it will merely slacken at about 1500.

move the line or point of origin in the opposite direction.

Thus, the speed of the current flowing in the direction of the nontidal current is increased by an amount equal to the magnitude of the nontidal current, and the speed of the current flowing in the opposite direction is decreased by an equal amount. In Figure 917a, a nontidal current is represented both in direction and speed by the vector AO. Since this is greater than the speed of the tidal current in the opposite direction, the point A is outside the ellipse. The direction and speed of the combined tidal and nontidal currents at any time is represented by a vector from A to that point on the curve representing the given time, and can be scaled from the graph. The strongest and weakest currents may no longer be in the directions of the maximum and minimum of the tidal current. In a reversing current (Figure 917b), the effect is to advance the time of one slack, and to retard the following one. If the speed of the nontidal current exceeds that of the reversing tidal current, the resultant current flows continuously in one direction without coming to a slack. In this case, the speed varies from a maximum to a minimum and back to a maximum in each tidal cycle. In Figure 917b, the horizontal line A represents slack water if only tidal currents are present. Line B represents the effect of a 0.5 knot nontidal ebb, and line C the effect of a 1.0 knot nontidal ebb. With the condition shown at C there is only one flood each tidal day. If the nontidal ebb were to increase to approximately 2 knots, there would be no flood, two maximum ebbs and two minimum ebbs occurring during a tidal day.

918. Time Of Tidal Current And Time Of Tide

At many places where current and tide are both semidiurnal, there is a definite relationship between times of current and times of high and low water in the locality. Current atlases and notes on nautical charts often make use of this relationship by presenting for particular locations, the direction and speed of the current at each succeeding hour

after high and low water, at a place for which tide predictions are available.

Where there is considerable diurnal inequality in tide or current, or where the type of current differs from the type of tide, the relationship is not constant, and it may be hazardous to try to predict the times of current from times of tide. Note the current curve for Unimak Pass in the Aleutians in Figure 915a. It shows the current as predicted in the tidal current tables. Predictions of high and low waters in the tide tables might have led one to expect the current to change from flood to ebb in the late morning, whereas actually the current continued to run flood with some strength at that time.

Since the relationship between times of tidal current and tide is not everywhere the same, and may be variable at the same place, one should exercise extreme caution in using general rules. The belief that slacks occur at local high and low tides and that the maximum flood and ebb occur when the tide is rising or falling most rapidly may be approximately true at the seaward entrance to, and in the upper reaches of, an inland tidal waterway. But generally this is not true in other parts of inland waterways. When an inland waterway is extensive or its entrance constricted, the slacks in some parts of the waterway often occur midway between the times of high and low tide. Usually in such waterways the relationship changes from place to place as one progresses upstream, slack water getting progressively closer in time to the local tide maximum until at the head of tidewater (the inland limit of water affected by a tide) the slacks occur at about the times of high and low tide.

919. Relationship Between Speed Of Current And Range Of Tide

The speed of the tidal current is not necessarily consistent with the range of tide. It may be the reverse. For example, currents are weak in the Gulf of Maine where the tides are large, and strong near Nantucket Island and in Nantucket Sound where the tides are small. However, at any one place the speed of the current at strength of flood and ebb varies during the month in about the same proportion as the range of tide, and this relationship can be used to determine the relative strength of currents on any given day.

920. Variation Across An Estuary

In inland tidal estuaries the time of tidal current varies across the channel from shore to shore. On the average, the current turns earlier near shore than in midstream, where the speed is greater. Differences of half an hour to an hour are not uncommon, but the difference varies and the relationship may be nullified by the effect of nontidal flow.

The speed of the current also varies across the channel, usually being greater in midstream or midchannel than near shore, but in a winding river or channel the strongest currents occur near the concave shore, or the outside corner of the curve. Near the opposite (convex) shore the currents are weak or eddying.

921. Variation With Depth

In tidal rivers the subsurface current acting on the lower portion of a ship's hull may differ considerably from the surface current. An appreciable subsurface current may be present when the surface movement appears to be practically slack, and the subsurface current may even be flowing with appreciable speed in the opposite direction to the surface current.

In a tidal estuary, particularly in the lower reaches where there is considerable difference in density from top to bottom, the flood usually begins earlier near the bottom than at the surface. The difference may be an hour or two, or as little as a few minutes, depending upon the estuary, the location in the estuary, and freshet conditions. Even when the freshwater runoff becomes so great as to prevent the surface current from flooding, it may still flood below the surface. The difference in time of ebb from surface to bottom is normally small but subject to variation with time and location.

The ebb speed at strength usually decreases gradually from top to bottom, but the speed of flood at strength often is stronger at subsurface depths than at the surface.

922. Tidal Current Observations

Observations of current are made with sophisticated electronic **current meters**. Current meters are suspended from a buoy or anchored to the bottom with no surface marker at all. Very sensitive current meters measure and record deep ocean currents; these are later recovered by triggering a release mechanism with a signal from the surface. Untended current meters either record data internally or send it by radio to a base station on ship or land. The period of observation varies from a few hours to as long as 6 months.

TIDE AND CURRENT PREDICTION

923. Tidal Height Predictions

To measure tides, hydrographers select a reference level, or **datum**. Soundings shown on the largest scale charts are the vertical distances from this datum to the bottom. At any given time the actual depth is this charted depth plus the height of tide. In most places the reference level is some form of low water. But all low waters at a given place are not the same height, and the selected reference level is seldom the lowest tide occurring at the place. When lower tides occur, these are indicated in the tide tables by a negative sign. Thus, at a spot where the charted depth is 15 feet,

the actual depth is 15 feet plus the tidal height. When the tide is three feet, the depth is 15 + 3 = 18 feet. When it is (-) 1 foot, the depth is 15 - 1 = 14 feet. The actual depth can be less than the charted depth. In an area where there is a considerable range of tide (the difference between high water and low water), the height of tide might be an important consideration when using soundings to determine if the vessel is in safe water.

The heights given in the tide tables are predictions, and when assumed conditions vary considerably, the predictions shown may be considerably in error. Heights lower than predicted can be anticipated when the atmospheric pressure is higher than normal, or when there is a persistent strong offshore wind. The greater the range of tide, the less reliable are the predictions for both height and current.

924. Tidal Heights

The nature of the tide at any place can best be determined by observation. The predictions in tide tables and the tidal data on nautical charts are based upon detailed observations at specific locations, instead of theoretical predictions.

Tidal elevations are usually observed with a continuously recording gage. A year of observations is the minimum length desirable for determining the harmonic constants used in prediction. For establishing mean sea level and long-term changes in the relative elevations of land and sea, as well as for other special uses, observations have been made over periods of 20, 30, and even 120 years at important locations. Observations for a month or less will establish the type of tide and suffice for comparison with a longer series of observations to determine tidal differences and constants.

Mathematically, the variations in the lunar and solar tide-producing forces, such as those due to changing phase, distance, and declination, are considered as separate constituent forces, and the harmonic analysis of observations reveals the response of each constituent of the tide to its corresponding force. At any one place this response remains constant and is shown for each constituent by **harmonic constants** which are in the form of a phase angle for the time relation and an amplitude for the height. Harmonic constants are used in making technical studies of the tide and in tidal predictions on computers. The tidal predictions in most published tide tables are produced by computer.

925. Meteorological Effects

The foregoing discussion of tidal behavior assumes normal weather conditions. However, sea level is also affected by wind and atmospheric pressure. In general, onshore winds raise the level and offshore winds lower it, but the amount of change varies at different places. During periods of low atmospheric pressure, the water level tends to be higher than normal. For a stationary low, the increase in elevation can be found by the formula

$$R0=0.01(1010 - P),$$

in which R_0 is the increase in elevation in meters and P is the atmospheric pressure in millibars. This is equal approximately to 1 centimeter per millibar depression, or about 1 foot (13.6 inches) per inch depression. For a moving low, the increase in elevation is given by the formula

$$R= \frac{R_0}{1 - \frac{C^2}{gh}}$$

in which R is the increase in elevation in feet, R_0 is the increase in meters for a stationary low, C is the rate of motion of the low in feet per second, g is the acceleration due to gravity (32.2 feet per second per second), and h is the depth of water in feet.

Where the range of tide is very small, the meteorological effect may sometimes be greater than the normal tide. Where a body of water is large in area but shallow, high winds can push the water from the windward to the lee shore, creating much greater local differences in water levels than occurs normally, and partially or completely masking the tides. The effect is dependent on the configuration and depth of the body of water relative to the wind direction, strength and duration.

926 Tidal Current Predictions

Tidal currents are due primarily to tidal action, but other causes are often present. The **Tidal Current Tables** give the best prediction of total current. Following heavy rains or a drought, a river's current prediction may be considerably in error. Current alters a vessel's course and velocity. Set and drift may vary considerably over different parts of a harbor, because differences in bathymetry from place to place affect current. Since this is usually an area where small errors in a vessel's position are crucial, a knowledge of predicted currents, particularly in reduced visibility, is important. Strong currents occur mostly in narrow passages connecting larger bodies of water. Currents of more than 5 knots are sometimes encountered in the Golden Gate at San Francisco, and currents of more than 13 knots sometimes occur at Seymour Narrows, British Columbia.

In straight portions of rivers and channels, the strongest currents usually occur in the middle of the channel. In curved portions the swiftest currents (and deepest water) usually occur near the outer edge of the curve. Countercurrents and eddies may occur on either side of the main current of a river or narrow passage, especially near obstructions and in bights.

In general, the range of tide and the velocity of tidal current are at a minimum in the open ocean or along straight coasts. The greatest tidal effects are usually encountered in estuaries, bays, and other coastal indentations. A vessel proceeding along a indented coast may encounter a set toward or away from the shore; a similar set is seldom experienced along a straight coast.

927. Prediction Tables

Predictions of tides and currents have been published by the National Ocean Service (NOS) since 1853. They are published annually, and are supplemented by tidal current charts.

Usually, tidal information is obtained from tide and tidal current tables, or from specialized computer software or calculators. However, if these are not available, or if they do not include information at a desired place, the mariner may be able to obtain locally the **mean high water lunitidal interval** or the **high water full and change**. The approximate time of high water can be found by adding either interval to the time of transit (either upper or lower) of the moon. Low water occurs approximately 1/4 tidal day (about $6^h\ 12^m$) before and after the time of high water. The actual interval varies somewhat from day to day, but approximate results can be obtained in this manner. Similar information for tidal currents (**lunicurrent interval**) is seldom available.

PUBLICATIONS FOR PREDICTING TIDES AND CURRENTS

928. Tide Tables

Tide tables for various parts of the world are published in 4 volumes by the National Ocean Service. These volumes are:

- Central and Western Pacific Ocean and Indian Ocean
- East Coast of North and South America (including Greenland)
- Europe and West Coast of Africa
- West Coast of North and South America (including Hawaiian Islands)

A small separate volume, the Alaskan Supplement, is also published.

Each volume has 5 common tables:

- **Table 1** contains a complete list of the predicted times and heights of the tide for each day of the year at a number of places designated as **reference stations**.
- **Table 2** gives tidal differences and ratios which can be used to modify the tidal information for the reference stations to make it applicable to a relatively large number of **subordinate stations**.
- **Table 3** provides information for finding the approximate height of the tide at any time between high water and low water.
- **Table 4** is a sunrise-sunset table at five-day intervals for various latitudes from 76°N to 60°S (40°S in one volume).
- **Table 5** provides an adjustment to convert the local mean time of table 4 to zone or standard time.

For the East Coast and West Coast volumes, each contains a table 6, a moonrise and moonset table; table 7 for conversion from feet to centimeters; table 8, a table of estimated tide prediction accuracies; a glossary of terms; and an index to stations. Each table is preceded by a complete explanation. Sample problems are given where necessary. The inside back cover of each volume contains a calendar of critical astronomical data to help explain the variations of the tide during each month and throughout the year.

929. Tide Predictions For Reference Stations

For each day, the date and day of week are given, and the time and height of each high and low water are listed in chronological order. Although high and low waters are not labeled as such, they can be distinguished by the relative heights given immediately to the right of the times. If two high tides and two low tides occur each tidal day, the tide is semidiurnal. Since the tidal day is longer than the civil day (because of the revolution of the moon eastward around the earth), any given tide occurs later each day. Because of later times of corresponding tides from day to day, certain days have only one high water or only one low water.

930. Tide Predictions For Subordinate Stations

For each subordinate station listed, the following information is given:

1. **Number**. The stations are listed in geographical order and assigned consecutive numbers. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in locating the entry in table 2.
2. **Place**. The list of places includes both subordinate and reference stations; the latter appear in bold type.
3. **Position**. The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south, and the longitude east or west, depending upon the letters (N, S, E, W) next above the entry. These may not be the same as those at the top of the column.
4. **Differences**. The differences are to be applied to the predictions for the reference station, shown in capital letters above the entry. Time and height differences are given separately for high and low waters. Where differences are omitted, they are either unreliable or unknown.
5. **Ranges**. Various ranges are given, as indicated in the tables. In each case this is the difference in height between high water and low water for the tides indicated.
6. **Mean tide level**. This is the average between mean low and mean high water, measured from chart datum.

The **time difference** is the number of hours and minutes to be applied to the reference station time to find the

time of the corresponding tide at the subordinate station. This interval is added if preceded by a plus sign (+) and subtracted if preceded by a minus sign (-). The results obtained by the application of the time differences will be in the zone time of the time meridian shown directly above the difference for the subordinate station. Special conditions occurring at a few stations are indicated by footnotes on the applicable pages. In some instances, the corresponding tide falls on a different date at reference and subordinate stations.

Height differences are shown in a variety of ways. For most entries, separate height differences in feet are given for high water and low water. These are applied to the height given for the reference station. In many cases a ratio is given for either high water or low water, or both. The height at the reference station is multiplied by this ratio to find the height at the subordinate station. For a few stations, both a ratio and difference are given. In this case the height at the reference station is first multiplied by the ratio, and the difference is then applied. An example is given in each volume of tide tables. Special conditions are indicated in the table or by footnote. For example, a footnote indicates that “Values for the Hudson River above George Washington Bridge are based upon averages for the six months May to October, when the fresh-water discharge is a minimum.”

931. Finding Height Of Tide At Any Time

Table 3 provides means for determining the approximate height of tide at any time. It assumes that plotting height versus time yields a sine curve. Actual values may vary from this. The explanation of the table contains directions for both mathematical and graphic solutions. Though the mathematical solution is quicker, if the vessel’s ETA changes significantly, it will have to be done for the new ETA. Therefore, if there is doubt about the ETA, the graphical solution will provide a plot of predictions for several hours and allow quick reference to the predicted height for any given time. This method will also quickly show at what time a given depth of water will occur. Figure 931a shows the OPNAV form used to calculate heights of tides. Figure 931b shows the importance of calculating tides in shallow water.

OPNAV 3530/40 (4-73)
HT OF TIDE

Date		
Location		
Time		
Ref Sta		
HW Time Diff		
LW Time Diff		
HW Ht Diff		
LW Ht Diff		
Ref Sta HW/LW Time		
HW/LW Time Diff		
Sub Sta HW/LW Time		
Ref Sta HW/LW Ht		
HW/LW Ht Diff		
Sub Sta HW/LW Ht		
Duration	**Rise**	
	Fall	
Time Fm	**Near**	
	Tide	
Range of Tide		
Ht of Neat Tide		
Corr Table 3		
Ht of Tide		
Charted Depth		
Depth of Water		
Draft		
Clearance		

Figure 931a. OPNAV 3530/40 Tide Form.

932. Tidal Current Tables

Tidal current tables are somewhat similar to tide tables, but the coverage is less extensive. NOS publishes 2 volumes on an annual basis: Atlantic Coast of North America, and Pacific Coast of North America and Asia. Each of the two volumes is arranged as follows:

- **Table 1** contains a complete list of predicted times of maximum currents and slack water, with the velocity (velocity) of the maximum currents, for a number of reference stations.
- **Table 2** gives differences, ratios, and other information related to a relatively large number of subordinate stations.
- **Table 3** provides information to determine the current’s velocity at any time between entries in tables 1 and 2.
- **Table 4** gives duration of slack, or the number of minutes the current does not exceed stated amounts, for various maximum velocities.
- **Table 5** (Atlantic Coast of North America only) gives information on rotary tidal currents.

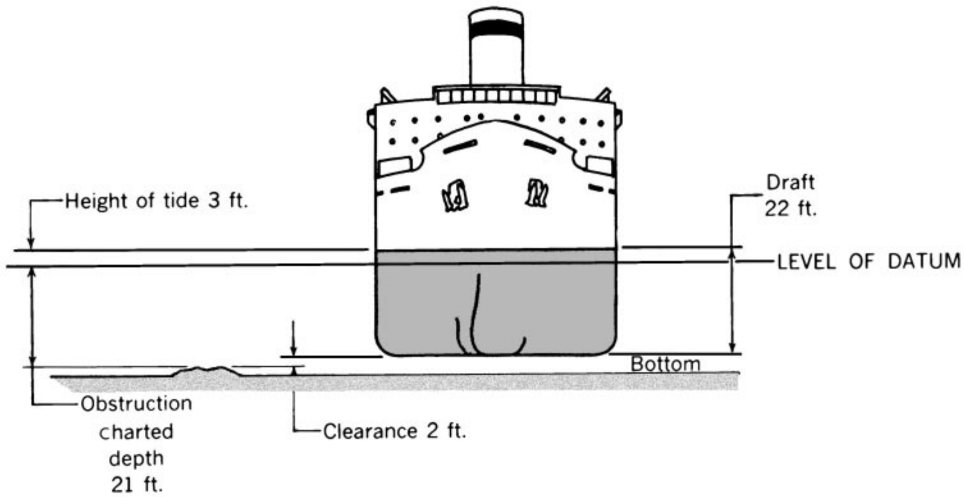


Figure 931b. Height of tide required to pass clear of charted obstruction.

Each volume also contains current diagrams and instructions for their use. Explanations and examples are given in each table.

The volumes also contain general descriptive information on wind-driven currents, combination currents, and information such as Gulf Stream currents for the east coast and coastal currents on the west coast.

933. Tidal Current Prediction For Reference Stations

For each day, the date and day of week are given; current information follows. If the cycle is repeated twice each tidal day, currents are semidiurnal. On most days there are four slack waters and four maximum currents, two floods (F) and two ebbs (E). However, since the tidal day is longer than the civil day, the corresponding condition occurs later each day, and on certain days there are only three slack waters or three maximum currents. At some places, the current on some days runs maximum flood twice, but ebb only once, a minimum flood occurring in place of the second ebb. The tables show this information.

934. Tidal Current Predictions For Subordinate Stations

For each subordinate station listed in table 2 of the tidal current tables, the following information is given:

1. **Number**. The stations are listed in geographical order and assigned consecutive numbers, as in the tide tables. Each volume contains an alphabetical station listing correlating the station with its consecutive number to assist in locating the entry in table 2.
2. **Place**. The list of places includes both subordinate and reference stations, the latter given in bold type.
3. **Position**. The approximate latitude and longitude are given to assist in locating the station. The latitude is north or south and the longitude east or west as indicated by the letters (N, S, E, W) next above the entry. The current given is for the center of the channel unless another location is indicated by the station name.
4. **Time difference**. Two time differences are tabulated. One is the number of hours and minutes to be applied to the tabulated times of slack water at the reference station to find the times of slack waters at the subordinate station. The other time difference is applied to the times of maximum current at the reference station to find the times of the corresponding maximum current at the subordinate station. The intervals, which are added or subtracted in accordance with their signs, include any difference in time between the two stations, so that the answer is correct for the standard time of the subordinate station. Limited application and special conditions are indicated by footnotes.
5. **Velocity ratios**. Speed of the current at the subordinate station is the product of the velocity at the reference station and the tabulated ratio. Separate ratios may be given for flood and ebb currents. Special conditions are indicated by footnotes.
6. **Average Speeds and Directions**. Minimum and maximum velocities before flood and ebb are listed for each station, along with the true directions of the flow. Minimum velocity is not always 0.0 knots.

935. Finding Velocity Of Tidal Current At Any Time

Table 3 of the tidal current tables provides means for determining the approximate velocity at any time. Directions are given in an explanation preceding the table. Figure 935 shows the OPNAV form used for current prediction.

936. Duration Of Slack Water

The predicted times of slack water listed in the tidal current tables indicate the instant of zero velocity. There is a period each side of slack water, however, during which the current is so weak that for practical purposes it may be considered negligible. Table 4 of the tidal current tables gives, for various maximum currents, the approximate period of time during which currents not exceeding 0.1 to 0.5 knots will be encountered. This period includes the last of the flood or ebb and the beginning of the following flood or ebb; that is, half of the duration will be before and half after the time of slack water.

When there is a difference between the velocities of the maximum flood and ebb preceding and following the slack for which the duration is desired, it will be sufficiently accurate to find a separate duration for each maximum velocity and average the two to determine the duration of the weak current.

Of the two sub-tables of table 4, table A is used for all places except those listed for table B; table B is used for just the places listed and the stations in table 2 which are referred to them.

937. Additional Tide Prediction Publications

NOS also publishes a special Regional Tide and Tidal Current Table for New York Harbor to Chesapeake Bay, and a Tidal Circulation and Water Level Forecast Atlas for Delaware River and Bay.

938. Tidal Current Charts

Tidal Current charts present a comprehensive view of the hourly velocity of current in different bodies of water. They also provide a means for determining the current's velocity at various locations in these waters. The arrows show the direction of the current; the figures give the speed in knots at the time of spring tides. A weak current is defined as less than 0.1 knot. These charts depict the flow of the tidal current under normal weather conditions. Strong winds and freshets, however, may cause nontidal currents, considerably modifying the velocity indicated on the charts.

Tidal Current charts are provided (1994) for Boston Harbor, Charleston Harbor SC, Long Island Sound and Block Island Sound, Narragansett Bay, Narragansett Bay to Nantucket Sound, Puget Sound (Northern Part), Puget Sound (Southern Part), Upper Chesapeake Bay, and Tampa Bay.

The tidal current's velocity varies from day to day as a function of the phase, distance, and declination of the moon. Therefore, to obtain the velocity for any particular day and hour, the spring velocities shown on the charts must be modified by correction factors. A correction table-given in the charts can be used for this purpose.

OPNAV 3530/40 (4-73) VEL OF CURRENT
Date
Location
Time
Ref Sta
Time Diff Stack Water
Time Diff Max Current
Vel Ratio Max Flood
Vel Ratio Max Ebb
Flood Dir
Ebb Dir
Ref Sta Stack Water Time
Time Diff
Local Sta Stack Water Time
Ref Sta Max Current Time
Time Diff
Local Sta Max Current Time
Ref Sta Max Current Vel
Vel Ratio
Local Sta Max Current Vel
Int Between Slack and Desired Time
Int Between Slack and Max Current
Max Current
Factor Table 3
Velocity
Direction

Figure 935. OPNAV 3530/41 Current Form.

All of the charts except Narragansett Bay require the use of the annual Tidal Current Tables. Narragansett Bay requires use of the annual Tide Tables.

939. Current Diagrams

A current diagram is a graph showing the velocity of the current along a channel at different stages of the tidal current cycle. The current tables include diagrams for Martha’s Vineyard and Nantucket Sounds (one diagram); East River, New York; New York Harbor; Delaware Bay and River (one diagram); and Chesapeake Bay.

On Figure 939, each vertical line represents a given instant identified by the number of hours before or after slack water at The Narrows. Each horizontal line represents a distance from Ambrose Channel entrance, measured along the usually traveled route. The names along the left margin are placed at the correct distances from Ambrose Channel entrance. The current is for the center of the channel opposite these points. The intersection of any vertical line with any horizontal line represents a given moment in the current cycle at a given place in the channel. If this intersection is in a shaded area, the current is flooding; if in an unshaded area, it is ebbing. The velocity can be found by interpolation between the numbers given in the diagram. The given values are averages. To find the value at any time, multiply the velocity found from the diagram by the ratio of maximum velocity of the current involved to the maximum shown on the diagram. If the diurnal inequality is large, the accuracy can be improved by altering the width of the shaded area to fit conditions. The diagram covers 1 1/2 current cycles, so that the right 1/3 duplicates the left 1/3.

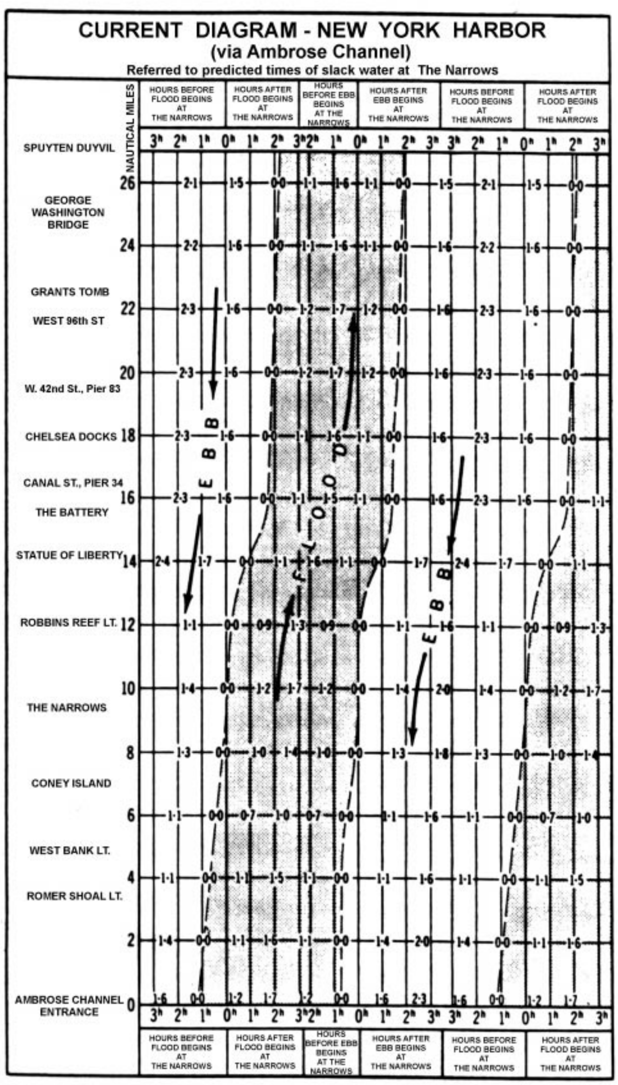


Figure 939. Current diagram for New York Harbor.

Use table 1 or 2 to determine the current for a single station. The current diagrams are intended for use in either of two ways: to determine a favorable time for passage through the channel and to find the average current to be expected during a passage through the channel. For both of these uses, a number of “velocity lines” are provided. When the appropriate line is transferred to the correct part of the diagram, the current to be encountered during passage is indicated along the line.

If the transferred velocity line is partly in a flood current area, all ebb currents (those increasing the ship’s velocity) are given a positive sign (+), and all flood currents a negative sign (-). A separate ratio should be determined for each current (flood or ebb), and applied to the entries for that current. In the Chesapeake Bay, it is common for an outbound vessel to encounter three or even four separate currents during passage. Under the latter condition, it is good practice to multiply each current taken from the diagram by the ratio for the current involved.

If the time of starting the passage is fixed, and the current during passage is desired, the starting time is identified in terms of the reference tidal cycle. The velocity line is then drawn through the intersection of this vertical time line and the horizontal line through the place. The average current is then determined in the same manner as when the velocity line is located as described above.

940. Computer Predictions

Until recently, tidal predictions were compiled only on mainframe or minicomputers and then put into hardcopy table form for the mariner. There are several types of commercial software available now for personal computers (PC’s) that provide digital versions of the NOS tide tables and also provide the capability to graph the tidal heights. The tabular information and graphs can be printed for the desired locations for pre-voyage planning. There are also several types of specialized hand-held calculators and tide clocks that can be used to predict tides for local areas.

Newer versions of PC software use the actual harmonic constants available for locations, the prediction equation,

and digital versions of table 2 in the Tide Tables to produce even more products for the navigator's use.

Emerging applications include integration of tidal prediction with positioning systems and vessel traffic systems which are now moving towards full use of GPS. In addition, some electronic chart systems are already able to integrate tide prediction information. Many of these new systems will also use real-time water level and current information. Active research also includes providing predictions of total water level that will include not only the tidal prediction component, but also the weather-related component.

CHAPTER 10

RADIO WAVES

ELECTROMAGNETIC WAVE PROPAGATION

1000. Source Of Radio Waves

Consider electric current as a flow of electrons along a conductor between points of differing potential. A **direct current** flows continuously in the same direction. This would occur if the polarity of the electromotive force causing the electron flow were constant, such as is the case with a battery. If, however, the current is induced by the relative motion between a conductor and a magnetic field, such as is the case in a rotating machine called a **generator**, then the resulting current changes direction in the conductor as the polarity of the electromotive force changes with the rotation of the generator's rotor. This is known as **alternating current**.

The energy of the current flowing through the conductor is either dissipated as heat (an energy loss proportional to both the current flowing through the conductor and the conductor's resistance) or stored in an electromagnetic field oriented symmetrically about the conductor. The orientation of this field is a function of the polarity of the source producing the current. When the current is removed from the wire, this electromagnetic field will, after a finite time, collapse back into the wire.

What would occur should the polarity of the current source supplying the wire be reversed at a rate which greatly exceeds the finite amount of time required for the electromagnetic field to collapse back upon the wire? In the case of rapid pole reversal, another magnetic field, proportional in strength but exactly opposite in magnetic orientation to the initial field, will be formed upon the wire. The initial magnetic field, its current source gone, cannot collapse back upon the wire because of the existence of this second, oriented electromagnetic field. Instead, it "detaches" from the wire and propagates out into space. This is the basic principle of a radio antenna, which transmits a wave at a frequency proportional to the rate of pole reversal and at a speed equal to the speed of light.

1001. Radio Wave Terminology

The magnetic field strength in the vicinity of a conductor is directly proportional to the magnitude of the current flowing through the conductor. Recall the discussion of alternating current above. A rotating generator produces current in the form of a sine wave. That is, the magnitude of the current varies as a function of the relative position of the rotating conductor and the stationary magnetic field used to induce the current. The current starts at zero, increases to a maximum as the rotor completes one quarter of its revolution, and falls to zero when the rotor completes one half of its revolution. The current then approaches a negative maximum; then it once again returns to zero. This cycle can be represented by a sine function.

The relationship between the current and the magnetic field strength induced in the conductor through which the current is flowing is shown in Figure 1001. Recall from the discussion above that this field strength is proportional to the magnitude of the current; that is, if the current is represented by a sine wave function, then so too will be the magnetic field strength resulting from that current. This characteristic shape of the field strength curve has led to the use of the term "wave" when referring to electromagnetic propagation. The maximum displacement of a peak from zero is called the **amplitude**. The forward side of any wave is called the **wave front**. For a nondirectional antenna, each wave proceeds outward as an expanding sphere (or hemisphere).

One **cycle** is a complete sequence of values, as from crest to crest. The distance traveled by the energy during one cycle is the **wavelength**, usually expressed in metric units (meters, centimeters, etc.). The number of cycles repeated during unit time (usually 1 second) is the **frequency**. This is given in **hertz** (cycles per second). A kilohertz (kHz) is 1,000 cycles per second. A megahertz (MHz) is 1,000,000 cycles per second. Wavelength and frequency are inversely proportional.

The **phase** of a wave is the amount by which the cycle

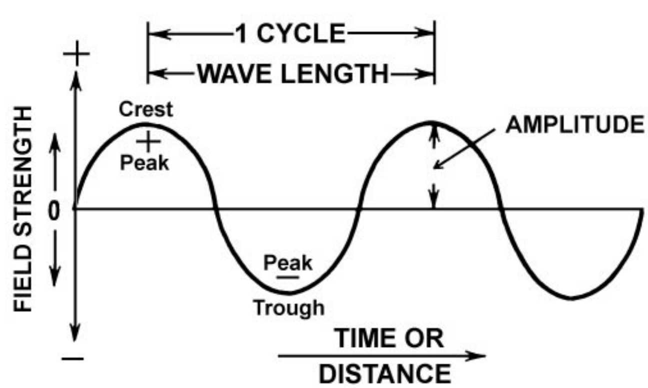


Figure 1001. Radio wave terminology.

has progressed from a specified origin. For most purposes it is stated in circular measure, a complete cycle being considered 360°. Generally, the origin is not important, principal interest being the phase relative to that of some other wave. Thus, two waves having crests 1/4 cycle apart are said to be 90° "out of phase." If the crest of one wave occurs at the trough of another, the two are 180° out of phase.

1002. Electromagnetic Spectrum

The entire range of electromagnetic radiation frequencies is called the **electromagnetic spectrum**. The frequency range suitable for radio transmission, the **radio spectrum**, extends from 10 kilohertz to 300,000 megahertz. It is divided into a number of bands, as shown in Table 1002. Below the radio spectrum, but overlapping it, is the audio frequency band, extending from 20 to 20,000 hertz. Above the radio spectrum are heat and infrared, the visible spectrum (light in its various colors), ultraviolet, X-rays, gamma rays, and cosmic rays. These are included in Table 1002. Waves shorter than 30 centimeters are usually called **microwaves**.

1003. Polarization

Radio waves produce both electric and magnetic fields. The direction of the electric component of the field is called the **polarization** of the electromagnetic field. Thus, if the electric component is vertical, the wave is said to be "vertically polarized," and if horizontal, "horizontally polarized." A wave traveling through space may be polarized in any direction. One traveling along the surface of the earth is always vertically polarized because the earth, a conductor, short-circuits any horizontal component. The magnetic field and the electric field are always mutually perpendicular.

1004. Reflection

When radio waves strike a surface, the surface reflects them in the same manner as light waves. Radio waves of all frequencies are reflected by the surface of the earth. The strength of the reflected wave depends upon grazing angle (the angle between the incident ray and the horizontal), type of polarization, frequency, reflecting properties of the surface, and divergence of the reflected ray. Lower frequency results in greater penetration. At very low frequencies, usable radio signals can be received some distance below the surface of the sea.

A phase change occurs when a wave is reflected from the surface of the earth. The amount of the change varies with the conductivity of the earth and the polarization of the wave, reaching a maximum of 180° for a horizontally polarized wave reflected from sea water (considered to have infinite conductivity). When direct waves (those traveling from transmitter to receiver in a relatively straight line, without reflection) and reflected waves arrive at a receiver, the total signal is the vector sum of the two. If the signals are in phase, they reinforce each other, producing a stronger signal. If there is a phase difference, the signals tend to cancel each other, the cancellation being complete if the phase difference is 180° and the two signals have the same amplitude. This interaction of waves is called **wave interference**. A phase difference may occur because of the change of phase of a reflected wave, or because of the longer path followed by it. The second effect decreases with greater distance between transmitter and receiver, for under these conditions the difference in path lengths is smaller. At lower frequencies there is no practical solution to interference caused in this way. For VHF and higher frequencies, the condition can be improved by elevating the antenna, if the

Band	Abbreviation	Range of frequency	Range of wavelength
Audio frequency	AF	20 to 20,000 Hz	15,000,000 to 15,000 m
Radio frequency	RF	10 kHz to 300,000 MHz	30,000 m to 0.1 cm
Very low frequency	VLF	10 to 30 kHz	30,000 to 10,000 m
Low frequency	LF	30 to 300 kHz	10,000 to 1,000 m
Medium frequency	MF	300 to 3,000 kHz	1,000 to 100 m
High frequency	HF	3 to 30 MHz	100 to 10 m
Very high frequency	VHF	30 to 300 MHz	10 to 1 m
Ultra high frequency	UHF	300 to 3,000 MHz	100 to 10 cm
Super high frequency	SHF	3,000 to 30,000 MHz	10 to 1 cm
Extremely high frequency	EHF	30,000 to 300,000 MHz	1 to 0.1 cm
Heat and infrared*		10^6 to 3.9×10^8 MHz	0.03 to 7.6×10^{-5} cm
Visible spectrum*		3.9×10^8 to 7.9×10^8 MHz	7.6×10^{-5} to 3.8×10^{-5} cm
Ultraviolet*		7.9×10^8 to 2.3×10^{10} MHz	3.8×10^{-5} to 1.3×10^{-6} cm
X-rays*		$2..0\times10^9$ to 3.0×10^{13} MHz	1.5×10^{-5} to 1.0×10^{-9} cm
Gamma rays*		2.3×10^{12} to 3.0×10^{14} MHz	1.3×10^{-8} to 1.0×10^{-10} cm
Cosmic rays*		$>4.8\times10^{15}$ MHz	$<6.2\times10^{-12}$ cm

* Values approximate.

Table 1002. Electromagnetic spectrum.

wave is vertically polarized. Additionally, interference at higher frequencies can be more nearly eliminated because of the greater ease of beaming the signal to avoid reflection.

Reflections may also occur from mountains, trees, and other obstacles. Such reflection is negligible for lower frequencies, but becomes more prevalent as frequency increases. In radio communication, it can be reduced by using directional antennas, but this solution is not always available for navigational systems.

Various reflecting surfaces occur in the atmosphere. At high frequencies, reflections take place from rain. At still higher frequencies, reflections are possible from clouds, particularly rain clouds. Reflections may even occur at a sharply defined boundary surface between air masses, as when warm, moist air flows over cold, dry air. When such a surface is roughly parallel to the surface of the earth, radio waves may travel for greater distances than normal The principal source of reflection in the atmosphere is the ionosphere.

1005. Refraction

Refraction of radio waves is similar to that of light waves. Thus, as a signal passes from air of one density to that of a different density, the direction of travel is altered. The principal cause of refraction in the atmosphere is the difference in temperature and pressure occurring at various heights and in different air masses.

Refraction occurs at all frequencies, but below 30 MHz the effect is small as compared with ionospheric effects, diffraction, and absorption. At higher frequencies, refraction in the lower layer of the atmosphere extends the radio horizon to a distance about 15 percent greater than the visible horizon. The effect is the same as if the radius of the earth were about one-third greater than it is and there were no refraction.

Sometimes the lower portion of the atmosphere becomes stratified. This stratification results in nonstandard temperature and moisture changes with height. If there is a marked temperature inversion or a sharp decrease in water vapor content with increased height, a horizontal radio duct may be formed. High frequency radio waves traveling horizontally within the duct are refracted to such an extent that they remain within the duct, following the curvature of the earth for phenomenal distances. This is called **super-refraction**. Maximum results are obtained when both transmitting and receiving antennas are within the duct. There is a lower limit to the frequency affected by ducts. It varies from about 200 MHz to more than 1,000 MHz.

At night, surface ducts may occur over land due to cooling of the surface. At sea, surface ducts about 50 feet thick may occur at any time in the trade wind belt. Surface ducts 100 feet or more in thickness may extend from land out to sea when warm air from the land flows over the cooler ocean surface. Elevated ducts from a few feet to more than 1,000 feet in thickness may occur at elevations of 1,000 to 5,000 feet, due to the settling of a large air mass. This is a frequent occurrence in Southern California and certain areas of the Pacific Ocean.

A bending in the horizontal plane occurs when a groundwave crosses a coast at an oblique angle. This is due to a marked difference in the conducting and reflecting properties of the land and water over which the wave travels. The effect is known as **coastal refraction** or **land effect**.

1006. The Ionosphere

Since an atom normally has an equal number of negatively charged electrons and positively charged protons, it is electrically neutral. An **ion** is an atom or group of atoms which has become electrically charged, either positively or negatively, by the loss or gain of one or more electrons.

Loss of electrons may occur in a variety of ways. In the atmosphere, ions are usually formed by collision of atoms with rapidly moving particles, or by the action of cosmic rays or ultraviolet light. In the lower portion of the atmosphere, recombination soon occurs, leaving a small percentage of ions. In thin atmosphere far above the surface of the earth, however, atoms are widely separated and a large number of ions may be present. The region of numerous positive and negative ions and unattached electrons is called the **ionosphere**. The extent of ionization dependsupon the kinds of atoms present in the atmosphere, the density of the atmosphere, and the position relative to the sun (time of day and season). After sunset, ions and electrons recombine faster than they are separated, decreasing the ionization of the atmosphere.

An electron can be separated from its atom only by the application of greater energy than that holding the electron. Since the energy of the electron depends primarily upon the kind of an atom of which it is a part, and its position relative to the nucleus of that atom, different kinds of radiation may cause ionization of different substances.

In the outermost regions of the atmosphere, the density is so low that oxygen exists largely as separate atoms, rather than combining as molecules as it does nearer the surface of the earth. At great heights the energy level is low and ionization from solar radiation is intense. This is known as the **F layer**. Above this level the ionization decreases because of the lack of atoms to be ionized. Below this level it decreases because the ionizing agent of appropriate energy has already been absorbed. During daylight, two levels of maximum F ionization can be detected, the F_2 layer at about 125 statute miles above the surface of the earth, and the F_1 layer at about 90 statute miles. At night, these combine to form a single F layer.

At a height of about 60 statute miles, the solar radiation not absorbed by the F layer encounters, for the first time, large numbers of oxygen molecules. A new maximum ionization occurs, known as the **E layer**. The height of this layer is quite constant, in contrast with the fluctuating F layer. At night the E layer becomes weaker by two orders of magnitude.

Below the E layer, a weak D layer forms at a height of

about 45 statute miles, where the incoming radiation encounters ozone for the first time. The D layer is the principal source of absorption of HF waves, and of reflection of LF and VLF waves during daylight.

1007. The Ionosphere And Radio Waves

When a radio wave encounters a particle having an electric charge, it causes that particle to vibrate. The vibrating particle absorbs electromagnetic energy from the radio wave and radiates it. The net effect is a change of polarization and an alteration of the path of the wave. That portion of the wave in a more highly ionized region travels faster, causing the wave front to tilt and the wave to be directed toward a region of less intense ionization.

Refer to Figure 1007a, in which a single layer of the ionosphere is considered. Ray 1 enters the ionosphere at such an angle that its path is altered, but it passes through and proceeds outward into space. As the angle with the horizontal decreases, a critical value is reached where ray 2 is bent or reflected back toward the earth. As the angle is still further decreased, such as at 3, the return to earth occurs at a greater distance from the transmitter.

A wave reaching a receiver by way of the ionosphere is called a **skywave**. This expression is also appropriately applied to a wave reflected from an air mass boundary. In common usage, however, it is generally associated with the ionosphere. The wave which travels along the surface of the earth is called a **groundwave**. At angles greater than the critical angle, no skywave signal is received. Therefore, there is a minimum distance from the transmitter at which skywaves can be received. This is called the

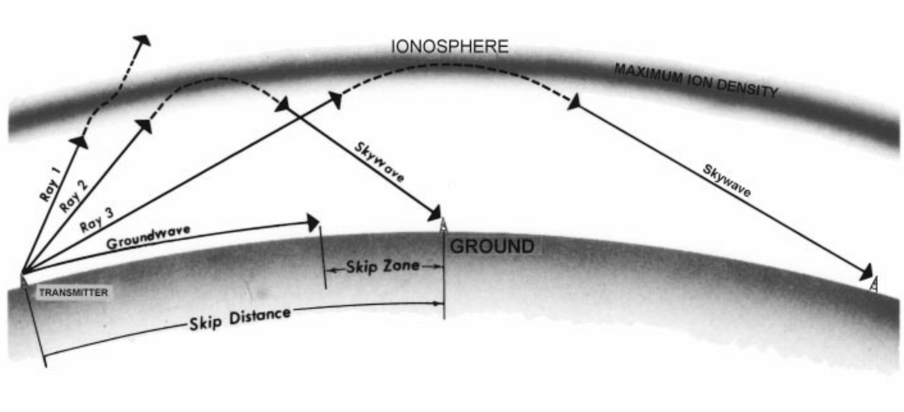


Figure 1007a. The effect of the ionosphere on radio waves.

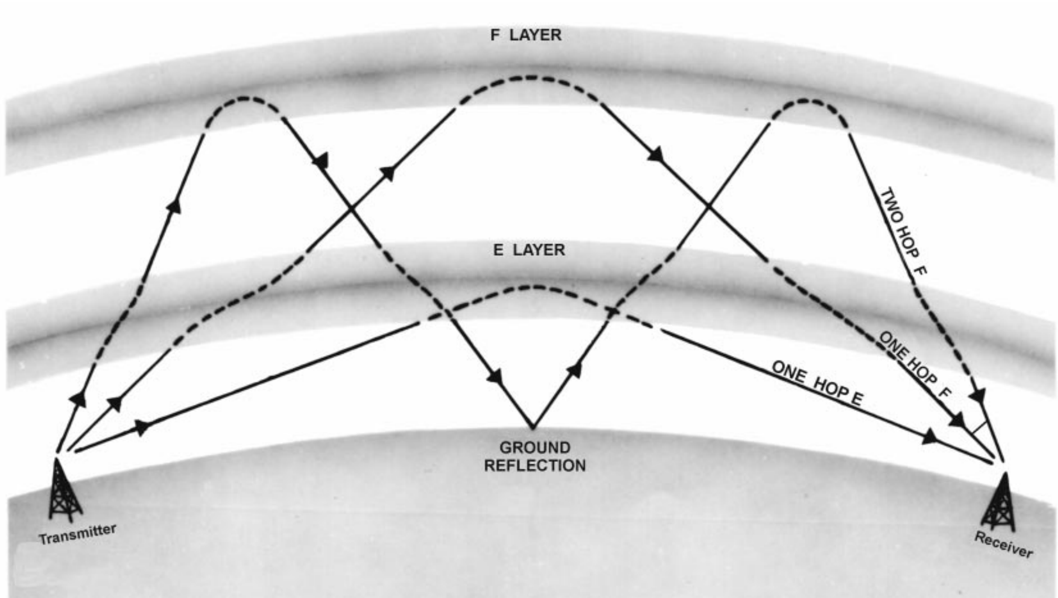


Figure 1007b. Various paths by which a skywave signal might be received.

skip distance, shown in Figure 1007a. If the groundwave extends out for less distance than the skip distance, a skip zone occurs, in which no signal is received.

The critical radiation angle depends upon the intensity of ionization, and the frequency of the radio wave. As the frequency increases, the angle becomes smaller. At frequencies greater than about 30 MHz virtually all of the energy penetrates through or is absorbed by the ionosphere. Therefore, at any given receiver there is a maximum usable frequency if skywaves are to be utilized. The strongest signals are received at or slightly below this frequency. There is also a lower practical frequency beyond which signals are too weak to be of value. Within this band the optimum frequency can be selected to give best results. It cannot be too near the maximum usable frequency because this frequency fluctuates with changes of intensity within the ionosphere. During magnetic storms the ionosphere density decreases. The maximum usable frequency decreases, and the lower usable frequency increases. The band of usable frequencies is thus narrowed. Under extreme conditions it may be completely eliminated, isolating the receiver and causing a radio blackout.

Skywave signals reaching a given receiver may arrive by any of several paths, as shown in Figure 1007b. A signal which undergoes a single reflection is called a "one-hop" signal, one which undergoes two reflections with a ground reflection between is called a "two-hop" signal, etc. A "multihop" signal undergoes several reflections. The layer at which the reflection occurs is usually indicated, also, as "one-hop E," "two-hop F," etc.

Because of the different paths and phase changes occurring at each reflection, the various signals arriving at a receiver have different phase relationships. Since the density of the ionosphere is continually fluctuating, the strength and phase relationships of the various signals may undergo an almost continuous change. Thus, the various signals may reinforce each other at one moment and cancel each other at the next, resulting in fluctuations of the strength of the total signal received. This is called **fading**. This phenomenon may also be caused by interaction of components within a single reflected wave, or changes in its strength due to changes in the reflecting surface. Ionospheric changes are associated with fluctuations in the radiation received from the sun, since this is the principal cause of ionization. Signals from the F layer are particularly erratic because of the rapidly fluctuating conditions within the layer itself.

The maximum distance at which a one-hop E signal can be received is about 1,400 miles. At this distance the signal leaves the transmitter in approximately a horizontal direction. A one-hop F signal can be received out to about 2,500 miles. At low frequencies groundwaves extend out for great distances.

A skywave may undergo a change of polarization during reflection from the ionosphere, accompanied by an alteration in the direction of travel of the wave. This is called **polarization error**. Near sunrise and sunset, when rapid changes are occurring in the ionosphere, reception may become erratic and polarization error a maximum. This is called **night effect**.

1008. Diffraction

When a radio wave encounters an obstacle, its energy is reflected or absorbed, causing a shadow beyond the obstacle. However, some energy does enter the shadow area because of diffraction. This is explained by Huygens' principle, which states that every point on the surface of a wave front is a source of radiation, transmitting energy in all directions ahead of the wave. No noticeable effect of this principle is observed until the wave front encounters an obstacle, which intercepts a portion of the wave. From the edge of the obstacle, energy is radiated into the shadow area, and also outside of the area. The latter interacts with energy from other parts of the wave front, producing alternate bands in which the secondary radiation reinforces or tends to cancel the energy of the primary radiation. Thus, the practical effect of an obstacle is a greatly reduced signal strength in the shadow area, and a disturbed pattern for a short distance outside the shadow area. This is illustrated in Figure 1008.

The amount of diffraction is inversely proportional to the frequency, being greatest at very low frequencies.

1009. Absorption And Scattering

The amplitude of a radio wave expanding outward through space varies inversely with distance, weakening with increased distance. The decrease of strength with distance is called **attenuation**. Under certain conditions the attenuation is greater than in free space.

A wave traveling along the surface of the earth loses a certain amount of energy to the earth. The wave is diffracted downward and absorbed by the earth. As a result of this absorption, the remainder of the wave front tilts downward, resulting in further absorption by the earth. Attenuation is greater over a surface which is a poor conductor. Relatively little absorption occurs over sea water, which is an excellent conductor at low frequencies, and low frequency groundwaves travel great distances over water.

A skywave suffers an attenuation loss in its encounter with the ionosphere. The amount depends upon the height and composition of the ionosphere as well as the frequency of the radio wave. Maximum ionospheric absorption occurs at about 1,400 kHz.

In general, atmospheric absorption increases with frequency. It is a problem only in the SHF and EHF frequency range. At these frequencies, attenuation is further increased by scattering due to reflection by oxygen, water vapor, water droplets, and rain in the atmosphere.

1010. Noise

Unwanted signals in a receiver are called **interference**. The intentional production of such interference to obstruct

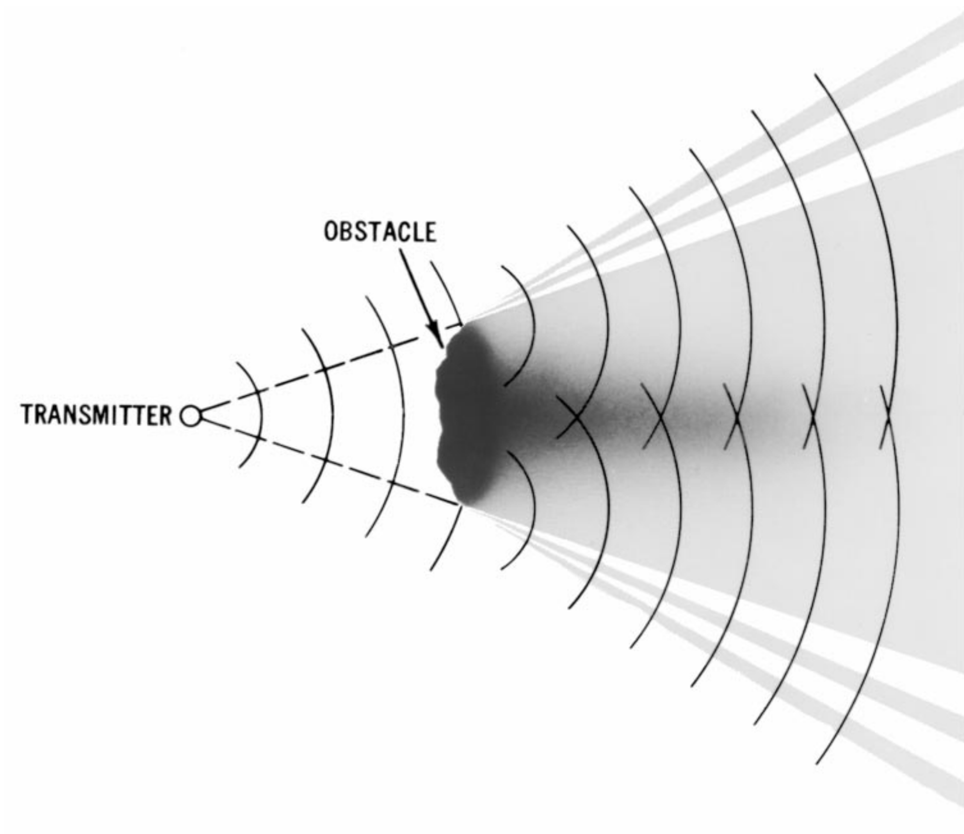


Figure 1008. Diffraction.

communication is called **jamming**. Unintentional interference is called **noise**.

Noise may originate within the receiver. Hum is usually the result of induction from neighboring circuits carrying alternating current. Irregular crackling or sizzling sounds may be caused by poor contacts or faulty components within the receiver. Stray currents in normal components causes some noise. This source sets the ultimate limit of sensitivity that can be achieved in a receiver. It is the same at any frequency.

Noise originating outside the receiver may be either man-made or natural. Man-made noises originate in electrical appliances, motor and generator brushes, ignition systems, and other sources of sparks which transmit electromagnetic signals that are picked up by the receiving antenna.

Natural noise is caused principally by discharge of static electricity in the atmosphere. This is called **atmospheric noise**, atmospherics, or static. An extreme example is a thunderstorm. An exposed surface may acquire a considerable charge of static electricity. This may be caused by friction of water or solid particles blown against or along such a surface. It may also be caused by splitting of a water droplet which strikes the surface, one part of the droplet requiring a positive charge and the other a negative charge. These charges may be transferred to the surface. The charge tends to gather at points and ridges of the conducting surface, and when it accumulates to a sufficient extent to overcome the insulating properties of the atmosphere, it discharges into the atmosphere. Under suitable conditions this becomes visible and is known as St. Elmo's fire, which is sometimes seen at mastheads, the ends of yardarms, etc.

Atmospheric noise occurs to some extent at all frequencies but decreases with higher frequencies. Above about 30 MHz it is not generally a problem.

1011. Antenna Characteristics

Antenna design and orientation have a marked effect upon radio wave propagation. For a single-wire antenna, strongest signals are transmitted along the perpendicular to the wire, and virtually no signal in the direction of the wire. For a vertical antenna, the signal strength is the same in all horizontal directions. Unless the polarization undergoes a change during transit, the strongest signal received from a vertical transmitting antenna occurs when the receiving antenna is also vertical.

For lower frequencies the radiation of a radio signal takes place by interaction between the antenna and the ground. For a vertical antenna, efficiency increases with greater length of the antenna. For a horizontal antenna, efficiency increases with greater distance between antenna and ground. Near-maximum efficiency is attained when

this distance is one-half wavelength. This is the reason for elevating low frequency antennas to great heights. However, at the lowest frequencies, the required height becomes prohibitively great. At 10 kHz it would be about 8 nautical miles for a half-wavelength antenna. Therefore, lower frequency antennas are inherently inefficient. This is partly offset by the greater range of a low frequency signal of the same transmitted power as one of higher frequency.

At higher frequencies, the ground is not used, both conducting portions being included in a dipole antenna. Not only can such an antenna be made efficient, but it can alsobe made sharply directive, thus greatly increasing the strength of the signal transmitted in a desired direction.

The power received is inversely proportional to the square of the distance from the transmitter, assuming there is no attenuation due to absorption or scattering.

1012. Range

The range at which a usable signal is received depends upon the power transmitted, the sensitivity of the receiver, frequency, route of travel, noise level, and perhaps other factors. For the same transmitted power, both the groundwave and skywave ranges are greatest at the lowest frequencies, but this is somewhat offset by the lesser efficiency of antennas for these frequencies. At higher frequencies, only direct waves are useful, and the effective range is greatly reduced. Attenuation, skip distance, ground reflection, wave interference, condition of the ionosphere, atmospheric noise level, and antenna design all affect the distance at which useful signals can be received.

1013. Radio Wave Propagation

Frequency is an important consideration in radio wave propagation. The following summary indicates the principal effects associated with the various frequency bands, starting with the lowest and progressing to the highest usable radio frequency.

Very Low Frequency (VLF, 10 to 30 kHz): The VLF signals propagate between the bounds of the ionosphere and the earth and are thus guided around the curvature of the earth to great distances with low attenuation and excellent stability. Diffraction is maximum. Because of the long wavelength, large antennas are needed, and even these are inefficient, permitting radiation of relatively small amounts of power. Magnetic storms have little effect upon transmission because of the efficiency of the "earth-ionosphere waveguide." During such storms, VLF signals may constitute the only source of radio communication over great distances. However, interference from atmospheric noise may be troublesome. Signals may be received from below the surface of the sea.

Low Frequency (LF, 30 to 300 kHz): As frequency is increased to the LF band and diffraction decreases, there is greater attenuation with distance, and range for a given power output falls off rapidly. However, this is partly offset by more efficient transmitting antennas. LF signals are most stable within groundwave distance of the transmitter. A wider bandwidth permits pulsed signals at 100 kHz. This allows separation of the stable groundwave pulse from the variable skywave pulse up to 1,500 km, and up to 2,000 km for overwater paths. The frequency for Loran C is in the LF band. This band is also useful for radio direction finding and time dissemination.

Medium Frequency (MF, 300 to 3,000 kHz): Groundwaves provide dependable service, but the range for a given power is reduced greatly. This range varies from about 400 miles at the lower portion of the band to about 15 miles at the upper end for a transmitted signal of 1 kilowatt. These values are influenced, however, by the power of the transmitter, the directivity and efficiency of the antenna, and the nature of the terrain over which signals travel. Elevating the antenna to obtain direct waves may improve the transmission. At the lower frequencies of the band, skywaves are available both day and night. As the frequency is increased, ionospheric absorption increases to a maximum at about 1,400 kHz. At higher frequencies the absorption decreases, permitting increased use of skywaves. Since the ionosphere changes with the hour, season, and sunspot cycle, the reliability of skywave signals is variable. By careful selection of frequency, ranges of as much as 8,000 miles with 1 kilowatt of transmitted power are possible, using multihop signals. However, the frequency selection is critical. If it is too high, the signals penetrate the ionosphere and are lost in space. If it is too low, signals are too weak. In general, skywave reception is equally good by day or night, but lower frequencies are needed at night. The standard broadcast band for commercial stations (535 to 1,605 kHz) is in the MF band.

High Frequency (HF, 3 to 30 MHz): As with higher medium frequencies, the groundwave range of HF signals is limited to a few miles, but the elevation of the antenna may increase the direct-wave distance of transmission. Also, the height of the antenna does have an important effect upon skywave transmission because the antenna has an "image" within the conducting earth. The distance between antenna and image is related to the height of the antenna, and this distance is as critical as the distance between elements of an antenna system. Maximum usable frequencies fall generally within the HF band. By day this may be 10 to 30 MHz, but during the night it may drop to 8 to 10 MHz. The HF band is widely used for ship-to-ship and ship-to-shore communication.

Very High Frequency (VHF, 30 to 300 MHz): Communication is limited primarily to the direct wave, or the direct wave plus a ground-reflected wave. Elevating the antenna to increase the distance at which direct waves can be used results in increased distance of reception, even though some wave interference between direct and ground-reflected waves is present. Diffraction is much less than with lower frequencies, but it is most evident when signals cross sharp mountain peaks or ridges. Under suitable conditions, reflections from the ionosphere are sufficiently strong to be

useful, but generally they are unavailable. There is relatively little interference from atmospheric noise in this band. Reasonably efficient directional antennas are possible with VHF. The VHF band is much used for communication.

Ultra High Frequency (UHF, 300 to 3,000 MHz): Skywaves are not used in the UHF band because the ionosphere is not sufficiently dense to reflect the waves, which pass through it into space. Groundwaves and ground-reflected waves are used, although there is some wave interference. Diffraction is negligible, but the radio horizon extends about 15 percent beyond the visible horizon, due principally to refraction. Reception of UHF signals is virtually free from fading and interference by atmospheric noise. Sharply directive antennas can be produced for transmission in this band, which is widely used for ship-to-ship and ship-to-shore communication.

Super High Frequency (SHF, 3,000 to 30,000 MHz): In the SHF band, also known as the microwave or as the centimeter wave band, there are no skywaves, transmission being entirely by direct and ground-reflected waves. Diffraction and interference by atmospheric noise are virtually nonexistent. Highly efficient, sharply directive antennas can be produced. Thus, transmission in this band is similar to that of UHF, but with the effects of shorter waves being greater. Reflection by clouds, water droplets, dust particles, etc., increases, causing greater scattering, increased wave interference, and fading. The SHF band is used for marine navigational radar.

Extremely High Frequency (EHF, 30,000 to 300,000 MHz): The effects of shorter waves are more pronounced in the EHF band, transmission being free from wave interference, diffraction, fading, and interference by atmospheric noise. Only direct and ground-reflected waves are available. Scattering and absorption in the atmosphere are pronounced and may produce an upper limit to the frequency useful in radio communication.

1014. Regulation Of Frequency Use

While the characteristics of various frequencies are important to the selection of the most suitable one for any given purpose, these are not the only considerations. Confusion and extensive interference would result if every userhad complete freedom of selection. Some form of regulation is needed. The allocation of various frequency bands to particular uses is a matter of international agreement. Within the United States, the Federal Communications Commission has responsibility for authorizing use of particular frequencies. In some cases a given frequency is allocated to several widely separated transmitters, but only under conditions which minimize interference, such as during daylight hours. Interference between stations is further reduced by the use of channels, each of a narrow band of frequencies. Assigned frequencies are separated by an arbitrary band of frequencies that are not authorized for use. In the case of radio aids to navigation and ship communications bands of several channels are allocated, permitting selection of band and channel by the user.

1015. Types Of Radio Transmission

A series of waves transmitted at constant frequency and amplitude is called a continuous wave (CW). This cannot be heard except at the very lowest radio frequencies, when it may produce, in a receiver, an audible hum of high pitch.

Although a continuous wave may be used directly, as in radiodirection finding or Decca, it is more commonly modified in some manner. This is called **modulation**. When this occurs, the continuous wave serves as a carrier wave for information. Any of several types of modulation may be used.

In **amplitude modulation (AM)** the amplitude of the carrier wave is altered in accordance with the amplitude of a modulating wave, usually of audio frequency, as shown in Figure 1015a. In the receiver the signal is demodulated by removing the modulating wave and converting it back to its original form. This form of modulation is widely used in voice radio, as in the standard broadcast band of commercial broadcasting.

If the frequency instead of the amplitude is altered in accordance with the amplitude of the impressed signal, as shown in Figure 1015a, **frequency modulation (FM)** occurs. This is used for commercial FM radio broadcasts and the sound portion of television broadcasts.

Pulse modulation (PM) is somewhat different, there being no impressed modulating wave. In this form of transmission, very short bursts of carrier wave are transmitted, separated by relatively long periods of "silence," during which there is no transmission. This type of transmission, illustrated in Figure 1015b, is used in some common radio navigational aids, including radar and Loran-C.

1016. Transmitters

A radio transmitter consists essentially of (1) a power supply to furnish direct current, (2) an oscillator to convert direct current into radio-frequency oscillations (the carrier wave), (3) a device to control the generated signal, and (4) an amplifier to increase the output of the oscillator. For some transmitters a microphone is needed with a modulator and final amplifier to modulate the carrier wave. In addition, an antenna and ground (for lower frequencies) are needed to produce electromagnetic radiation. These components are illustrated diagrammatically in Figure 1016.

1017. Receivers

When a radio wave passes a conductor, a current is induced in that conductor. A radio receiver is a device which senses the power thus generated in an antenna, and transforms it into usable form. It is able to select signals of a single frequency (actually a narrow band of frequencies) from among the many which may reach the receiving antenna. The receiver is able to demodulate the signal and provide adequate amplification. The output of a receiver

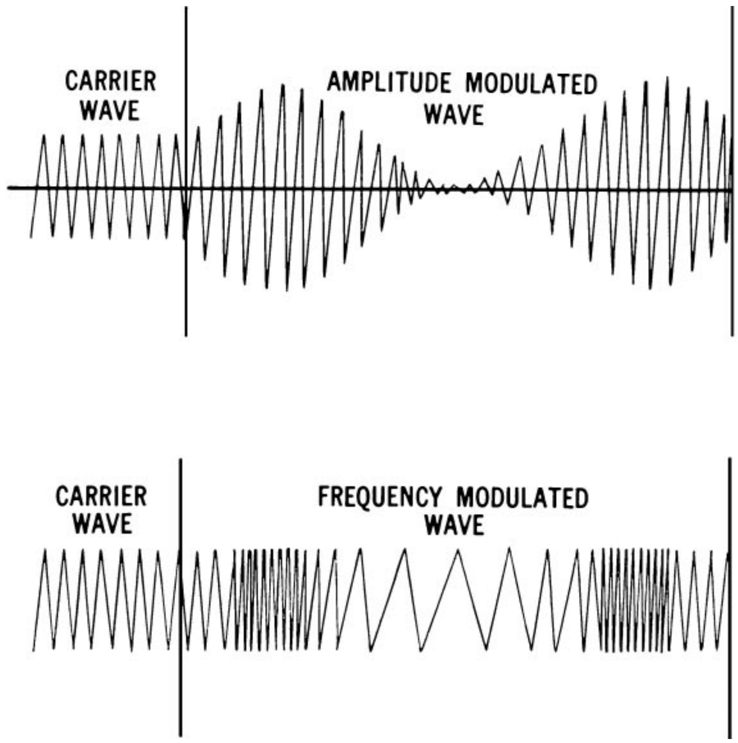


Figure 1015a. Amplitude modulation (upper figure) and frequency modulation (lower figure) by the same modulating wave.

Figure 1015b. Pulse modulation.

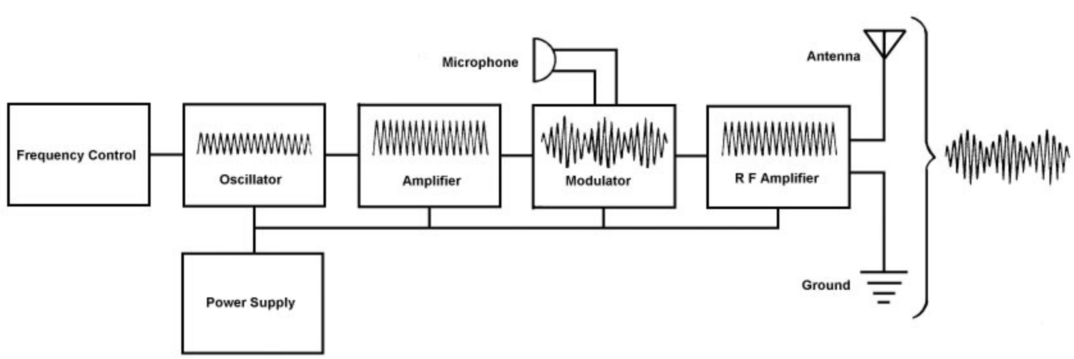


Figure 1016. Components of a radio transmitter.

may be presented audibly by earphones or loudspeaker; or visually on a dial, cathode-ray tube, counter, or other display. Thus, the useful reception of radio signals requires three components: (1) an antenna, (2) a receiver, and (3) a display unit.

Radio receivers differ mainly in (1) frequency range, the range of frequencies to which they can be tuned; (2) selectivity, the ability to confine reception to signals of the desired frequency and avoid others of nearly the same frequency; (3) sensitivity, the ability to amplify a weak signal to usable strength against a background of noise; (4) stability, the ability to resist drift from conditions or values to which set; and (5) fidelity, the completeness with which the essential characteristics of the original signal are reproduced. Receivers may have additional features such as an automatic frequency control, automatic noise limiter, etc.

Some of these characteristics are interrelated. For instance, if a receiver lacks selectivity, signals of a frequency differing slightly from those to which the receiver is tuned may be received. This condition is called spillover, and the

resulting interference is called crosstalk. If the selectivity is increased sufficiently to prevent spillover, it may not permit receipt of a great enough band of frequencies to obtain the full range of those of the desired signal. Thus, the fidelity may be reduced.

A transponder is a transmitter-receiver capable of accepting the challenge of an interrogator and automatically transmitting an appropriate reply.

U.S. RADIONAVIGATION POLICY

1018. The Federal Radionavigation Plan

The Federal Radionavigation Plan (FRP) is produced by the U.S. Departments of Defense and Transportation. It establishes government policy on electronic navigation systems, ensuring consideration of national interests and efficient use of resources. It presents an integrated Federal plan for all common-use civilian and military Radionavigation systems, outlines approaches for consolidation of systems, provides information and schedules, defines and clarifies new or unresolved issues, and provides a focal point for user input. The FRP is a review of existing and planned radionavigation systems used in air, space, land, and marine navigation. It is available from the National Technical Information Service, Springfield, Virginia, 22161.

The first edition of the FRP was released in 1980 as part of a Presidential report to Congress. It marked the first time that a joint Department of Transportation/Department of Defense plan had been developed for systems used by both departments. The FRP has had international impact on navigation systems; it has been distributed to the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Association of Lighthouse Authorities (IALA), and other international organizations.

During a national emergency, any or all of the systems may be discontinued due to a decision by the National Command Authority (NCA). The NCA's policy is to continue to operate radionavigation systems as long as the U.S. and its allies derive greater benefit than adversaries. Operating agencies may shut down systems or change signal formats and characteristics during such an emergency.

The plan is reviewed continually and updated biennially. Industry, advisory groups, and other interested parties provide input. The plan considers governmental responsibilities for national security, public safety, and transportation system economy. It is the official source of radionavigation systems policy and planning for the United States. Systems covered by the FRP include, Radiobeacons, Omega, TACAN, MLS, GPS, Loran C, VOR/VOR-DME/VORTAC, ILS, and Transit.

1019. Individual System Plans

In order to meet both civilian and military needs, the federal government has established a number of different navigation systems. Each system utilized the latest technology available at the time of implementation and has been upgraded as technology and resources permitted. The FRP addresses the length of time each system should be part of the system mix. The 1992 FRP sets forth the following system policy guidelines:

RADIOBEACONS: Both maritime and aeronautical radiobeacons provide the civilian community with a low-cost, medium accuracy navigation system. They will remain part of the radionavigation mix at least until the year 2000. Those radiobeacons suitable for supporting Differential GPS (DGPS) will remain well into the next century. Many of the remaining maritime radiobeacons may be discontinued after the year 2000.

LORAN C: Loran C provides navigation, location, and timing services for both civil and military air, land, and sea users. It is the federally provided navigation system for the maritime Coastal Confluence Zone; it is also a supplemental air navigation system. The Loran C system serving the continental U.S., Alaska, and coastal areas with the exception of Hawaii, is expected to remain in place through the year 2015. Military requirements for Loran C ended in 1994, and U.S.-maintained stations overseas and in Hawaii will be phased out. Discussions between the U.S. and foreign governments may result in continuation of certain overseas stations after termination of the military requirements.

OMEGA: Omega serves civilian and military maritime and air navigation. The military requirement for Omega ended in 1994; the system may be maintained for civil users at least until the year 2005. Replacement of equipment at some stations may result in disruption or reduction of service in some areas. Also, the Omega system relies on support from several foreign nations whose cooperation may not be forthcoming

TRANSIT: The Transit satellite system will end operations in December 1996.

GPS: The Global Positioning System, or GPS, will be the military's primary radionavigation system well into the next century. It is operated by the U.S. Air Force, and it will provide two basic levels of positioning service.

Standard Positioning Service (SPS) is a positioning and timing service which will provide horizontal positioning accuracies of 100 meters (2 drms, 95% probability) and 300 meters

(99.99% probability). **Precise Positioning Service** (PPS) will provide extremely accurate positioning to only military users.

DIFFERENTIAL GPS: DGPS services are planned by several DOT agencies to enhance civilian navigation without reliance on the PPS. The Coast Guard operates marine DGPS in U.S. coastal waters. DGPS is a system in which differences between observed and calculated GPS signals are broadcast to users using marine radiobeacons. The Coast Guard is implementing DGPS service in all U.S. coastal waters, beginning with important ports and harbors, to include Hawaii and the Great Lakes. It will provide 4-20 meter continuous accuracy.

A Memorandum of Agreement between DOD and DOT for radionavigation planning became effective in 1979. It was updated in 1984 and again in 1990. This agreement recognizes the joint responsibility of both agencies to provide cost-effective navigation systems for both military and civilian users, and requires the cooperation of both agencies in navigation systems planning.

Many factors influence the choice of navigation systems, which must satisfy an extremely diverse group of users. International agreements must be honored. The current investment in existing systems by both government and users must be considered. The full life-cycle cost of each system must be considered. No system will be phased out without consideration of all these factors. The FRP recognizes thatGPS may not meet the needs of all users; therefore, some systems are currently being evaluated independently of GPS. When GPS is fully implemented and evaluated, a further review will determine which systems to retain and which to phase out. The goal is to meet all military and civilian requirements with the minimum number of systems.

The Departments of Defense and Transportation continually evaluate the components which make up the federally provided and maintained radionavigation system. Several factors influence the decision on the proper mix of systems; cost, military utility, accuracy requirements, and user requirements all drive the problem of allocating scarce resources to develop and maintain marine navigation systems. The lowering cost and increasing accuracy of the Global Positioning System increase its attractiveness as the primary navigation method of the future for both military and civilian use. However, the popularity of GPS with navigation planners masks the fact that it is still much more expensive to the user than other radionavigation systems such as loran and omega, and many civilian mariners may balk at the cost of conversion. Planners' uncertainties over the future of the older navigation systems, especially in a time of shrinking resources, will contribute to the uncertainty which will mark the next five years in radionavigation planning and development.

RADIO DIRECTION FINDING

1020. Introduction

Medium frequency radio direction finders on board vessels enable measurement of the bearings of marine radiobeacons, aeronautical radiobeacons, and some commercial radio stations. This is the simplest use of radio waves in navigation.

Depending upon the design of the radio direction finder (RDF), the bearings of the radio transmissions are measured as relative bearings, or as both relative and true bearings. In one design, the true bearing dial is manually set with respect to the relative bearing dial, in accordance with the ship's heading. In another design, the true bearing dial is rotated electrically in accordance with a course input from the gyrocompass.

Radiobeacons established primarily for mariners are known as **marine radiobeacons**; beacons established primarily for airmen are known as **aeronautical radiobeacons**; other beacons established for both classes of user are sometimes known as **aeromarine radiobeacons**. The most common type of marine radiobeacon transmits radio waves of approximately uniform strength in all directions. These omnidirectional beacons are known as **circular radiobeacons**.

Except for calibration, radiobeacons operate continuously, regardless of weather conditions.

Simple combinations of dots and dashes are used for station identification. Where applicable, the Morse equivalent character or characters are shown in conjunction with the station characteristic. All radiobeacons superimpose the characteristic on a carrier wave which is on continuously during the period of transmission. This extends the usefulness of marine radiobeacons to an airborne or marine user of an automatic radio direction finder (ADF). Users of the "aural null" type radio direction finder notice no change. A 10-second dash is incorporated in the characteristic signal to enable the user of the aural null type of radio direction finder to refine the bearing.

Aeronautical radiobeacons are sometimes used by marine navigators for determining lines of position when marine radiobeacons are not available. Since it is not possible to predict the extent to which land effect may render the bearings of these beacons unreliable, they are not included in *Pub. 117, Radio Navigational Aids* unless they are within the marine frequency band and they are close enough to the coast to have negligible land effect. Their inclusion in *Pub. 117* does not imply that the beacons have been found reliable for marine use.

1021. Using Radio Direction Finders

Direction bearing measurement at the receiver is accomplished with a directional antenna. Nearly all antennas have some directional properties, but in the usual antenna used for radio communication, these properties are not sufficiently critical for navigational use.

Simple small craft RDF units usually have a ferrite rod antenna mounted directly on a receiver, with a 360° graduated scale. The rod can be rotated to the null and a reading taken off the scale, which is preset to either the boat's course or true north, according the navigator's wishes. Some small craft RDFs have a portable hand-held combination ferrite rod and compass, with earphones to hear the null.

Two types of loop antenna are used in larger radio direction finders. In one of these, the crossed loop type, two loops are rigidly mounted in such manner that one is placed at 90° to the other. The relative output of the two antennas is related to the orientation of each with respect to the direction of travel of the radio wave, and is measured by a device called a goniometer. This is the type antenna used in an automatic direction finder. In the other variation, the rotating loop type, a single loop is kept in rapid rotation by means of a motor. The antenna output is shown on a cathode-ray tube, and the resulting display shows the direction of the signal.

1022. Errors of Radio Bearings

Bearings obtained by radio direction finder are subject to certain errors:

Quadrantal error: When radio waves arrive at a receiver, they are influenced somewhat by the immediate environment. An erroneous bearing results from currents induced in the direction finder antenna by re-radiation from the structural features of the vessel's superstructure and distortion of the radio wave front due to the physical dimensions and contour of the vessel's hull. This quadrantal error is a function of the relative bearing, normally being maximum for bearings broad on the bow and broad on the quarter. Its value for various bearings can be determined, and a calibration table made.

Coastal refraction: A radio wave crossing a coastline at an oblique angle undergoes a change of direction due to differences in conducting and reflecting properties of land and water. This is sometimes called **land effect**. It is avoided by not using, or regarding as of doubtful accuracy, bearings of waves which cross a shoreline at an oblique angle. Bearings making an angle of less than 15° to 20° with a shoreline should not be trusted. If the transmitter is near the coast, negligible error is introduced because of the short distance the waves travel before undergoing refraction.

Polarization error: The direction of travel of radio waves may undergo an alteration during the confused period near sunrise or sunset, when great changes are taking place in the ionosphere. This error is sometimes called night effect. The error can be minimized by averaging several readings, but any radio bearings taken during this period should be considered of doubtful accuracy.

Reciprocal bearings: Unless a radio direction finder has a vertical sensing wire, there is a possible 180° ambiguity in the reading. If such an error is discovered, one should take the reciprocal of the uncorrected reading, and apply the correction for the new direction. If there is doubt as to which of the two possible directions is the correct one, one should wait long enough for the bearing to change appreciably and take another reading. The transmitter should draw aft between readings. If the reciprocal is used, the station will appear to have drawn forward. A reciprocal bearing furnished by a direction finder station should not be used because the quadrantal error is not known, either on the given bearing or its reciprocal.

1023. Accuracy Of Radio Bearings

In general, good radio bearings should not be in error by more than 2° for distances under 150 nautical miles. However, conditions vary considerably, and skill is an important factor. By observing the technical instructions for the equipment and practicing frequently when results can be checked by visual observation or by other means, one can develop skill and learn to what extent radio bearings can be relied upon under various conditions.

Other factors affecting accuracy include range, the condition of the equipment, and the accuracy of the calibration. Errors in bearing can result if the selectivity of a radio direction finder is poor.

1024. Factors Affecting Maximum Range

The service range of a radiobeacon is determined by the strength of the radiated signal. Field strength requirements for a given service range vary with latitude, being higher in the southern latitudes. The actual useful range may vary considerably from the service range with different types of radio direction finders and during varying atmospheric conditions.

Sensitivity is a measure of the ability of a receiver to detect transmissions. The sensitivity of a radio direction finder determines the degree to which the full range capability of the radiobeacon system can be utilized.

Selectivity is a measure of the ability of a receiver to choose one frequency and reject all others. Selectivity varies with the type of receiver and its condition.

1025. Using RDF Bearings

Due to the many factors which enter into the transmission and reception of radio signals, a mariner cannot practically estimate his distance from a radiobeacon either by the strength of the signals received or by the time at which the signals were first heard.

By setting the ship's head toward the null, the navigator can steer toward the transmitter, and this is the most

common use of RDFs today. In reduced visibility it is unwise to head directly toward the station unless there is certain sea room. Soundings should be watched carefully when homing, and a good lookout should be kept.

Alternatively, bearings can be taken on two or more stations and the lines plotted to determine a fix. A single RDF bearing can, of course, be crossed with any other LOP. An RDF bearing crossed with a sounding curve can give a rough position in the absence of any other systems. For emergency use, an ordinary transistor radio tuned to a commercial station can provide a rough bearing if the location of the transmitter is known.

Before taking bearings on a commercial broadcasting station, the mariner should consider the following, all of which lead to errors:

1. The frequency of the commercial station may differ widely from the frequency for which the radio direction finder is calibrated.
2. The antenna may be remote from the broadcast station.
3. The commercial stations are usually inland.

Accordingly, the use of commercial broadcasting stations to obtain a direction finder bearing is not recommended for accurate navigation. If these stations are used, the mariner should recognize the limitations of the bearings obtained.

1026. Radio Direction Finder Stations

Radio direction finder stations are equipped with special apparatus to determine the direction of radio signals transmitted by ships. Many are for use only in emergencies, and none are now located in the U.S. See *Pub. 117, Radio Navigational Aids*, for a current worldwide list of RDF stations.

CHAPTER 11

SATELLITE NAVIGATION

INTRODUCTION

1100. Early Developments In Satellite Navigation

The idea that led to development of the satellite navigation systems dates back to 1957 and the first launch of an artificial satellite into orbit, Russia's Sputnik I. Dr. William H. Guier and Dr. George C. Wieffenbach at the Applied Physics Laboratory of the Johns Hopkins University were monitoring the famous "beeps" transmitted by the passing satellite. They plotted the received signals at precise intervals, and noticed that a characteristic Doppler curve emerged. Since celestial bodies followed fixed orbits, they reasoned that this curve could be used to describe the satellite orbit. Later, they demonstrated that they could determine all of the orbital parameters for a passing satellite by doppler observation of a single pass from a single fixed station. The doppler shift apparent while receiving a transmission from a passing satellite proved to be an effective measuring device for establishing the satellite orbit.

Dr. Frank T. McClure, also of the Applied Physics Laboratory, reasoned that if the satellite orbit was known, doppler shift measurements could be used to determine one's position on earth. His studies in support of this hypothesis earned him the first National Aeronautics and Space Administration award for important contributions to space development.

In 1958, the Applied Physics Laboratory proposed exploring the possibility of an operational satellite doppler navigation system. The Chief of Naval Operations then set forth requirements for such a system. The first successful launching of a prototype system satellite in April 1960 demonstrated the doppler system's operational feasibility.

1101. NAVSAT, The First Satellite Navigation System

The **Navy Navigation Satellite System** (**NAVSAT**, also known as **TRANSIT**) was the first operational satellite navigation system. The system's accuracy was better than 0.1 nautical mile anywhere in the world. It was used primarily for the navigation of surface ships and submarines; but it also had some applications in air navigation. It was also used in hydrographic surveying and geodetic position determination.

NAVSAT uses the doppler shift of radio signals transmitted from a satellite to measure the relative velocity between the satellite and the navigator. Knowing the satellite orbit precisely, the navigator's absolute position can be accurately determined from the time rate of change of range to the satellite.

The Johns Hopkins University Applied Physics Laboratory developed NAVSAT for the U. S. Navy. The operation of the system is under the control of the U. S. Navy Astronautics Group with headquarters at Point Mugu, California.

1102. System Configuration, Operation, And Termination

The NAVSAT consists of 10 orbiting satellites and 3 orbiting spares; a network of tracking stations continuously monitoring the satellites and updating the information they transmit; and the receivers and computers for processing signals.

Each satellite is in a nominally circular polar orbit at an approximate altitude of 600 nautical miles. There are usually five satellites operating in the system. Five satellites in orbit provide redundancy; the minimum constellation for system operation is four. This redundancy allows for an unexpected failure of a satellite and the relatively long period of time required to schedule, prepare, and launch a replacement satellite. This redundancy also provides for turning off a satellite when (on rare occasions) its orbital plane precesses near another satellite's plane, or when the timing (phasing) of several satellites in their orbits are temporarily such that many satellites pass nearly simultaneously near one of the poles.

Each satellite contains: (1) receiver equipment to accept injection data and operational commands from the ground, (2) a decoder for digitizing the data, (3) switching logic and memory banks for sorting and storing the digital data, (4) control circuits to cause the data to be read out at specific times in the proper format, (5) an encoder to translate the digital data to phase modulation, (6) ultra stable 5 MHz oscillators, and (7) 1.5-watt transmitters to broadcast the 150- and 400-MHz oscillator-regulated frequencies that carry the data to earth.

The transit launch program ended in 1988. According to the Federal Radionavigation Plan, the Navy will cease operation of NAVSAT by the end of 1996, as the new Global Positioning System (GPS) comes into operation.

THE GLOBAL POSITIONING SYSTEM

1103. Basic System Description

The Federal Radionavigation Plan has designated the Navigation System using Timing and Ranging (NAVSTAR) Global Positioning System (GPS) as the primary navigation system of the U.S. government. GPS is a spaced-based radio positioning system which provides suitably equipped users with highly accurate position, velocity, and time data. It consists of three major segments: a **space segment**, a **control segment**, and a **user segment**.

The space segment contains 24 satellites. Precise spacing of the satellites in orbit is arranged such that a minimum of four satellites are in view to a user at any time on a worldwide basis. Each satellite transmits signals on two radio frequencies, superimposed on which are navigation and system data. Included in this data is predicted satellite ephemeris, atmospheric propagation correction data, satellite clock error information, and satellite health data. This segment consists of 21 operational satellites with three satellites orbiting as active spares. The satellites orbit in six separate orbital planes. The orbital planes have an inclination relative to the equator of 55° and an orbital height of 20,200 km. The satellites complete an orbit approximately once every 12 hours.

GPS satellites transmit **pseudorandom noise (PRN)** sequence-modulated radio frequencies, designated L1 (1575.42 MHz) and L2 (1227.60 MHz). The satellite transmits both a **Coarse Acquisition Code** (C/A code) and a **Precision Code** (P code). Both the P and C/A codes are transmitted on the L1 carrier; only the P code is transmitted on the L2 carrier. Superimposed on both the C/A and P codes is the Navigation message. This message contains satellite ephemeris data, atmospheric propagation correction data, and satellite clock bias.

GPS assigns a unique C/A code and a unique P code to each satellite. This practice, known as **code division multiple access (CDMA)**, allows all satellites the use of a common carrier frequency while still allowing the receiver to determine which satellite is transmitting. CDMA also allows for easy user identification of each GPS satellite. Since each satellite broadcasts using its own unique C/A and P code combination, it can be assigned a unique **PRN sequence number**. This number is how a satellite is identified when the GPS control system communicates with users about a particular GPS satellite.

The control segment includes a **master control station** (MCS), a number of monitor stations, and ground antennas located throughout the world. The master control station, located in Colorado Springs, Colorado, consists of equipment and facilities required for satellite monitoring, telemetry, tracking, commanding, control, uploading, and navigation message generation. The monitor stations, located in Hawaii, Colorado Springs, Kwajalein, Diego Garcia, and Ascension Island, passively track the satellites, accumulating ranging data from the satellites' signals and relaying them to the MCS. The MCS processes this information to determine satellite position and signal data accuracy, updates the navigation message of each satellite and relays this information to the ground antennas. The ground antennas then transmit this information to the satellites. The ground antennas, located at Ascension Island, Diego Garcia, and Kwajalein, are also used for transmitting and receiving satellite control information.

The user segment is designed for different requirements of various users. These receivers can be used in high, medium, and low dynamic applications. An example of a low dynamic application would be a fixed antenna or slowly drifting marine craft. An example of a medium dynamic application would be a marine or land vehicle traveling at a constant controlled speed. Finally, an example of a high dynamic application would be a high performance aircraft or a spacecraft. The user equipment is designed to receive and process signals from four or more orbiting satellites either simultaneously or sequentially. The processor in the receiver then converts these signals to three-dimensional navigation information based on the World Geodetic System 1984 reference ellipsoid. The user segment can consist of stand-alone receivers or equipment that is integrated into another navigation system. Since GPS is used in a wide variety of applications, from marine navigation to land surveying, these receivers can vary greatly in function and design.

1104. System Capabilities

GPS provides multiple users with accurate, continuous, worldwide, all-weather, common-grid, three-dimensional positioning and navigation information.

To obtain a navigation solution of position (latitude, longitude, and altitude) and time (four unknowns), four satellites must be selected. The GPS user measures pseudorange and pseudorange rate by synchronizing and tracking the navigation signal from each of the four selected satellites. Pseudorange is the true distance between the satellite and the user plus an offset due to the user's clock bias. Pseudorange rate is the true slant range rate plus an offset due to the frequency error of the user's clock. By decoding the ephemeris data and system timing information on each satellite's signal, the user's receiver/processor can convert the pseudorange and pseudorange rate to three-dimensional position and velocity. Four measurements are necessary to solve for the three unknown components of position (or velocity) and the unknown user time (or frequency) bias.

The navigation accuracy that can be achieved by any user depends primarily on the variability of the errors in making pseudorange measurements, the instantaneous geometry of the satellites as seen from the user's location on Earth, and the presence of **Selective Avaliability** (SA). Selective Availability is discussed further below.

1105. Global Positioning System Basic Concepts

As discussed above, GPS measures distances between satellites in orbit and a receiver on or above the earth and computes spheres of position from those distances. The intersections of those spheres of position then determine the receiver's position.

The distance measurements described above are done by comparing timing signals generated simultaneously by the satellites' and receiver's internal clocks. These signals, characterized by a special wave form known as the pseudorandom code, are generated in phase with each other. The signal from the satellite arrives at the receiver following a time delay proportional to its distance traveled. This time delay is detected by the phase shift between the received pseudo-random code and the code generated by the receiver. Knowing the time required for the signal to reach the receiver from the satellite allows the receiver to calculate the distance from the satellite. The receiver, therefore, must be located on a sphere centered at the satellite with a radius equal to this distance measurement. The intersection of three spheres of position yields two possible points of receiver position. One of these points can be disregarded since it is hundreds of miles from the surface of the earth. Theoretically, then, only three time measurements are required to obtain a fix from GPS.

In practice, however, a fourth measurement is required to obtain an accurate position from GPS. This is due to receiver clock error. Timing signals travel from the satellite to the receiver at the speed of light; even extremely slight timing errors between the clocks on the satellite and in the receiver will lead to tremendous range errors. The satellite's atomic clock is accurate to 10^{-9} seconds; installing a clock that accurate on a receiver would make the receiver prohibitively expensive. Therefore, receiver clock accuracy is sacrificed, and an additional satellite timing measurement is made. The fix error caused by the inaccuracies in the receiver clock is reduced by simultaneously subtracting a constant timing error from four satellite timing measurements until a pinpoint fix is reached. This process is analogous to the navigator's plotting of a visual fix when bearing transmission error is present in his bearing repeater system. With that bearing error present, two visual LOP's will not intersect at a vessel's true position; there will be an error introduced due to the fixed, constant error in the bearing transmission process. There are two ways to overcome such an error. The navigator can buy extremely accurate (and expensive) bearing transmission and display equipment, or he can simply take a bearing to a third visual navigation aid. The resulting fix will not plot as a pinpoint (as it would were there no transmission error present); rather, it will plot as a triangle. The navigator can then apply a constant bearing correction to each LOP until the correction applied equals the bearing transmission error. When the correction applied equals the original transmission error, the resultant fix should plot as a pinpoint. The situation with GPS receiver timing inaccuracies is analogous; time measurement error simply replaces bearing measurement error in the analysis. Assuming that the satellite clocks are perfectly synchronized and the receiver clock's error is constant, the subtraction of that constant error from the resulting distance determinations will reduce the fix error until a "pinpoint" position is obtained. It is important to note here that the number of lines of position required to employ this technique is a function of the number of lines of position required to obtain a fix. In the two dimensional visual plotting scenario described above, only two LOP's were required to constitute a fix. The bearing error introduced another unknown into the process, resulting in three total unknowns (the x coordinate of position, the y coordinate of position, and the bearing error). Because of the three unknowns, three LOP's were required to employ this correction technique. GPS determines position in three dimensions; the presence of receiver clock error adds an additional unknown. Therefore, four timing measurements are required to solve for the resulting four unknowns.

1106. GPS Signal Coding

Two separate carrier frequencies carry the signal transmitted by a GPS satellite. The first carrier frequency (L1) transmits on 1575.42 MHz; the second (L2) transmits on 1227.60 MHz. The GPS signal consists of three separate messages: the P-code, transmitted on both L1 and L2; the C/A code, transmitted on L1 only; and a navigation data message. The P code and C/A code messages are divided into individual bits known as **chips**. The frequency at which bits are sent for each type of signal is known as the **chipping rate**. The chipping rate for the P-code is 10.23 MHz (10.23 $\times 10^6$ bits per second); for the C/A code, 1.023 MHz (1.023 $\times 10^6$ bits per second); and for the data message, 50 Hz (50 bits per second). The P and C/A codes **phase modulate** the carriers; the C/A code is transmitted at a phase angle of 90° from the P code. The periods of repetition for the C/A and P codes differ. The C/A code repeats once every millisecond; the P-code sequence repeats every seven days.

As stated above the GPS carrier frequencies are phase modulated. This is simply another way of saying that the digital "1's" and "0's" contained in the P and C/A codes are indicated along the carrier by a shift in the carrier phase. This is analogous to sending the same data along a carrier by varying its amplitude (amplitude modulation, or AM) or its frequency (frequency modulation, or FM). See Figure 1106a. In phase modulation, the frequency and the amplitude of the carrier are unchanged by the "information signal," and the digital information is transmitted by shifting the carrier's phase. The phase modulation employed by GPS is known as bi-phase shift keying (BPSK).

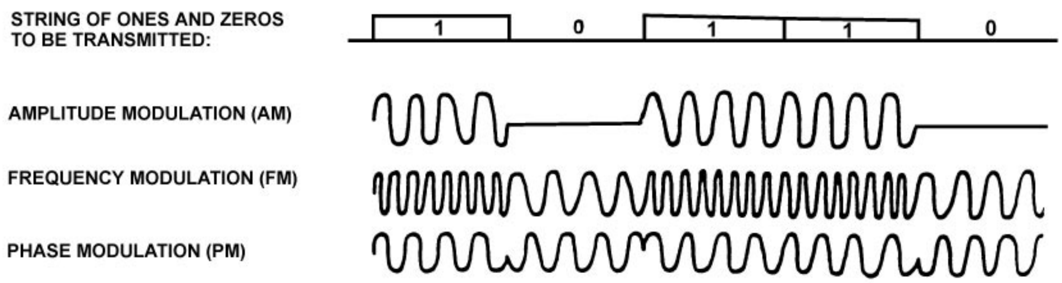


Figure 1106a. Digital data transmission with amplitude, frequency and phase modulation.

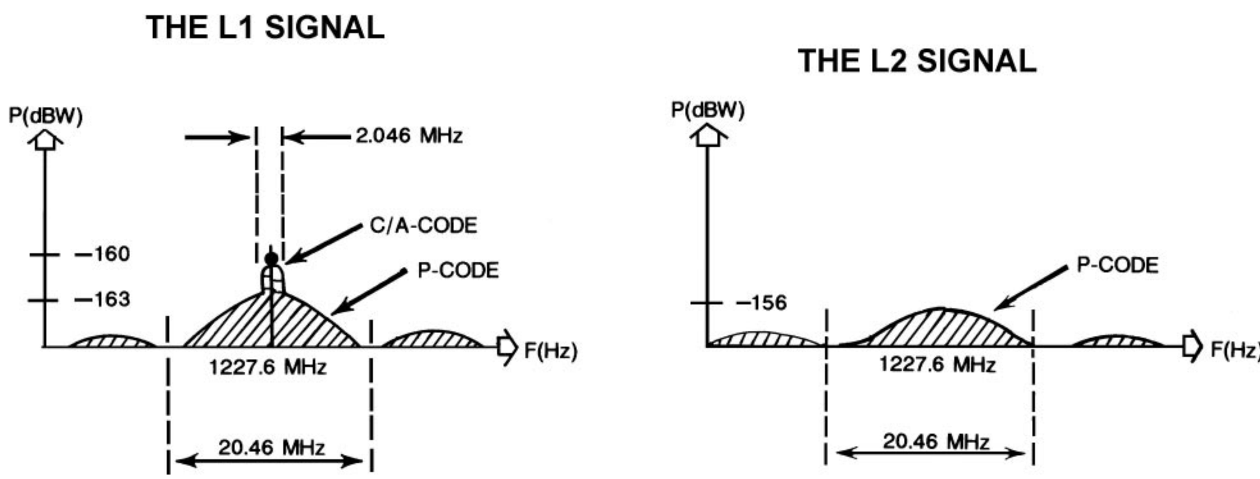


Figure 1106b. Modulation of the L1 and L2 carrier frequencies with the C/A and P code signals.

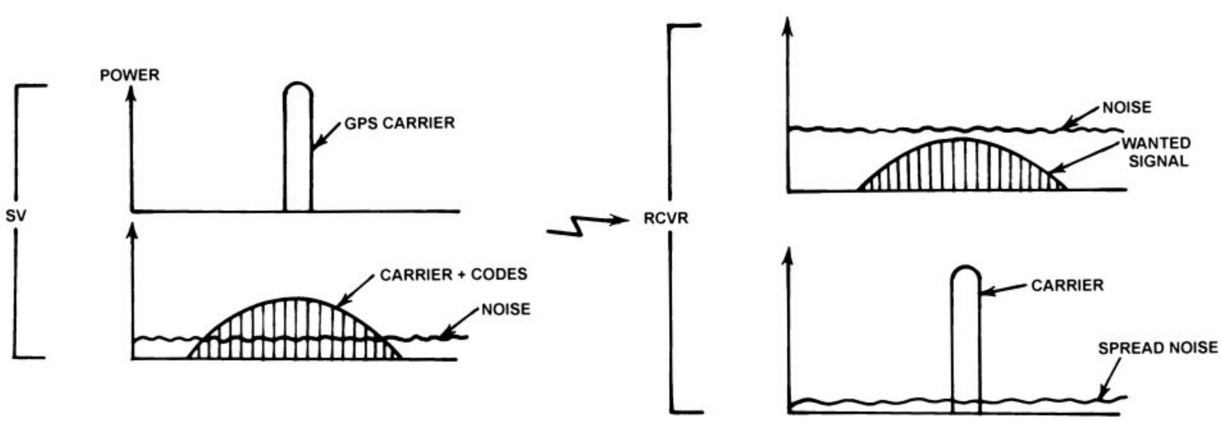


Figure 1106c. GPS signal spreading and recovery from satellite to receiver.

Due to this BPSK, the carrier frequency is "spread" about its center frequency by an amount equal to twice the "chipping rate" of the modulating signal. In the case of the P code, this spreading is equal to $(2 \times 10.23$ MHz$) = 20.46$ MHz. For the C/A code, the spreading is equal to $(2 \times 1.023$ MHz$) = 2.046$ MHz. See Figure 1106b. Note that the L1 carrier signal, modulated with both the P code and C/A code, is shaped differently from the L2 carrier, modulated with only the P code. This spreading of the carrier signal lowers the total signal strength below the thermal noise threshold present at the receiver. This effect is demonstrated in Figure 1106c. When the satellite signal is multiplied with the C/A and P codes generated by the receiver, the satellite signal will be collapsed into the original carrier frequency band. The signal power is then raised above the thermal noise level.

The navigation message is superimposed on both the P code and C/A code with a data rate of 50 bits per second (50 Hz.) The navigation message consists of 25 data frames, each frame consisting of 1500 bits. Each frame is divided into five subframes of 300 bits each. It will, therefore, take 30 seconds to receive one data frame and 12.5 minutes to receive all 25 frames. The navigation message contains GPS system time of transmission; a **hand over word (HOW)**, allowing the transition between tracking the C/A code to the P code; ephemeris and clock data for the satellite being tracked; and almanac data for the satellites in orbit. It also contains coefficients for ionospheric delay models used by C/A receivers and coefficients used to calculate Universal Coordinated Time (UTC).

1107. The Correlation Process

The correlation process compares the signal received with the signal generated internal to the receiver. It does this by comparing the square wave function of the received signal with the square wave function generated by the receiver. The computer logic of the receiver recognizes the square wave signals as either a +1 or a 0 depending on whether the signal is "on" or "off." The signals are processed and matched by using an **autocorrelation function**.

This process defines the necessity for a "pseudo-random code." The code must be repeatable (i.e., non-random) because it is in comparing the two signals that the receiver makes its distance calculations. At the same time, the code must be random for the correlation process to work; the randomness of the signals must be such that the matching process excludes all possible combinations except the combination that occurs when the generated signal is shifted a distance proportional to the received signal's time delay. These simultaneous requirements to be both repeatable (non-random) and random give rise to the description of "pseudo-random"; the signal has enough repeatability to enable the receiver to make the required measurement while simultaneously retaining enough randomness to ensure incorrect calculations are excluded.

1108. Precise Positioning Service And Standard Positioning Service

Two levels of navigational accuracy are provided by the GPS: the **Precise Positioning Service (PPS)** and the **Standard Positioning Service (SPS)**. GPS was designed, first and foremost, by the U.S. Department of Defense as a United States military asset; its extremely accurate positioning capability is an asset access to which the U.S. military would like to limit during time of war. Therefore, the PPS is available only to authorized users, mainly the U.S. military and authorized allies. SPS, on the other hand, is available worldwide to anyone possessing a GPS receiver. PPS, therefore, provides a more accurate position than does SPS.

Two cryptographic methods are employed to deny the PPS accuracy to civilian users: **selective availability (SA)**

SA/A-S Configuration	SIS Interface Conditions	PPS Users	SPS Users
SA Set to Zero A-S Off	P-Code, no errors C/A-Code, no errors	Full accuracy, spoofable	Full accuracy,* spoofable
SA at Non-Zero Value A-S Off	P-Code, errors C/A-Code, errors	Full accuracy, spoofable	Limited accuracy, spoofable
SA Set to Zero A-S On	Y-Code, no errors C/A-Code, no errors	Full accuracy, Not spoofable**	Full accuracy,*** spoofable
SA at Non-Zero Value A-S On	Y-Code, errors C/A-Code, errors	Full accuracy, Not spoofable**	Limited accuracy, spoofable

* "Full accuracy" defined as equivalent to a PPS-capable UE operated in a similar manner.
** Certain PPS-capable UE do not have P- or Y-code tracking abilities and remain spoofable despite A-S protection being applied
*** Assuming negligible accuracy degradation due to C/A-code operation (but more susceptible to jamming).

Figure 1108. Effect of SA and A-S on GPS accuracy.

and **anti-spoofing (A-S)**. SA operates by introducing controlled errors into both the C/A and P code signals. SA can be programmed to degrade the signals' accuracy even further during time of war, denying a potential adversary the ability to use GPS to nominal SPS accuracy. SA introduces two errors into the satellite signal: (1) The **epsilon error**: an error in satellite ephemeris data in the navigation message; and (2) **clock dither**: error introduced in the satellite atomic clocks' timing. The presence of SA is the largest source of error present in an SPS GPS position measurement.

Anti-spoofing is designed to negate any hostile imitation of GPS signals. The technique alters the P code into another code, designated the Y code. The C/A code remains unaffected. The U.S. employs this technique to the satellite signals at random times and without warning; therefore, civilian users are unaware when this P code transformation takes place. Since anti-spoofing is applied only to the P code, the C/A code is not protected and can be spoofed.

Only users employing the proper cryptographic devices can defeat both SA and anti-spoofing. Without these devices, the user will be subject to the accuracy degradation of SA and will be unable to track the Y code.

GPS PPS receivers can use either the P code or the C/A code, or both, in determining position. Maximum accuracy is obtained by using the P code on both L1 and L2. The difference in propagation delay is then used to calculate ionospheric corrections. The C/A code is normally used to acquire the satellite signal and determine the approximate P code phase. Then, the receiver locks on the P code for precise positioning (subject to SA if not cryptographically equipped). Some PPS receivers possess a clock accurate enough to track and lock on the P code signal without initially tracking the C/A code. Some PPS receivers can track only the C/A code and disregard the P code entirely. Since the C/A code is transmitted on only one frequency, the dual frequency ionosphere correction methodology is unavailable and a ionospheric modeling procedure is required to calculate the required corrections.

SPS receivers, as mentioned above, provide positions with a degraded accuracy. The A-S feature denies SPS users access to the P code when transformed to the Y code. Therefore, the SPS user cannot rely on access to the P code to measure propagation delays between L1 and L2 and compute ionospheric delay corrections. Consequently, the typical SPS receiver uses only the C/A code because it is unaffected by A-S. Since C/A is transmitted only on L1, the dual frequency method of calculating ionospheric corrections is unavailable; an ionospheric modeling technique must be used. This is less accurate than the dual frequency method; this degradation in accuracy is accounted for in the 100 meter accuracy calculation. Figure 1108 presents the effect on SA and A-S on different types of GPS measurements.

1109. GPS Receiver Operations

In order for the GPS receiver to navigate, it has to track satellite signals, make pseudorange measurements, and collect navigation data.

A typical satellite tracking sequence begins with the receiver determining which satellites are available for it to track. Satellite visibility is determined by user-entered predictions of position, velocity, and time, and by almanac information stored internal to the receiver. If no stored almanac information exists, then the receiver must attempt to locate and lock onto the signal from any satellite in view. When the receiver is locked onto a satellite, it can demodulate the navigation message and read the almanac information about all the other satellites in the constellation. A carrier tracking loop tracks the carrier frequency while a code tracking loop tracks the C/A and P code signals. The two tracking loops operate together in an iterative process to acquire and track satellite signals.

The receiver's carrier tracking loop will locally generate an L1 carrier frequency which differs from the satellite produced L1 frequency due to a doppler shift in the received frequency. This doppler offset is proportional to the relative velocity along the line of sight between the satellite and the receiver, subject to a receiver frequency bias. The carrier tracking loop adjusts the frequency of the receiver-generated frequency until it matches the incoming frequency. This determines the relative velocity between the satellite and the receiver. The GPS receiver uses this relative velocity to calculate the velocity of the receiver. This velocity is then used to aid the code tracking loop.

The code tracking loop is used to make pseudorange measurements between the GPS receiver and the satellites. The receiver's tracking loop will generate a replica of the targeted satellite's C/A code with estimated ranging delay. In order to match the received signal with the internally generated replica, two things must be done: 1) The center frequency of the replica must be adjusted to be the same as the center frequency of the received signal; and 2) the phase of the replica code must be lined up with the phase of the received code. The center frequency of the replica is set by using the doppler-estimated output of the carrier tracking loop. The receiver will then slew the code loop generated C/A code though a millisecond search window to correlate with the received C/A code and obtain C/A tracking.

Once the carrier tracking loop and the code tracking loop have locked onto the received signal and the C/A code has been stripped from the carrier, the navigation message is demodulated and read. This gives the receiver other information crucial to a pseudorange measurement. The navigation message also gives the receiver the handover word, the code that allows a GPS receiver to shift from C/A code tracking to P code tracking.

The handover word is required due to the long phase (seven days) of the P code signal. The C/A code repeats every millisecond, allowing for a relatively small search window. The seven day repeat period of the P code requires that the receiver be given the approximate P code phase to narrow its search window to a manageable time. The handover word pro-

vides this P code phase information. The handover word is repeated every subframe in a 30 bit long block of data in the navigation message. It is repeated in the second 30 second data block of each subframe. For some receivers, this handover word is unnecessary; they can acquire the P code directly. This normally requires the receiver to have a clock whose accuracy approaches that of an atomic clock. Since this greatly increases the cost of the receiver, most receivers for non-military marine use do not have this capability.

Once the receiver has acquired the satellite signals from four GPS satellites, achieved carrier and code tracking, and has read the navigation message, the receiver is ready to begin making pseudorange measurements. Recall that these measurements are termed *pseudorange* because a receiver clock offset makes them inaccurate; that is, they do not represent the true range from the satellite, only a range biased by a receiver clock error. This clock bias introduces a fourth unknown into the system of equations for which the GPS receiver must solve (the other three being the x coordinate, y coordinate, and z coordinate of the receiver position). Recall from the discussion in section 1103 that the receiver solves this clock bias problem by making a fourth pseudorange measurement, resulting in a fourth equation to allow solving for the fourth unknown. Once the four equations are solved, the receiver has an estimate of the receiver's position in three dimensions and of GPS time. The receiver then converts this position into coordinates referenced to an earth model based on the World Geodetic System (1984).

1110. User Range Errors And Geometric Dilution Of Precision

There are two formal position accuracy requirements for GPS:

1) The PPS spherical position accuracy shall be 16 meters SEP (spherical error probable) or better.

2) The SPS user two dimensional position accuracy shall be 100 meters 2 drms or better.

Assume that a universal set of GPS pseudorange measurements results in a set of GPS position measurements. The accuracy of these measurements will conform to a normal (i.e. values symmetrically distributed around a mean of zero) probability function because the two most important factors affecting accuracy, the **geometric dilution of precision (GDOP)** and the **user equivalent range error (UERE)**, are continuously variable.

The UERE is the error in the measurement of the pseudoranges from each satellite to the user. The UERE is the product of several factors, including the clock stability, the predictability of the satellite's orbit, errors in the 50 Hz navigation message, the precision of the receiver's correlation process, errors due to atmospheric distortion and the calculations to compensate for it, and the quality of the satellite's signal. The UERE, therefore, is a random error which is the function of errors in both the satellites and the user's receiver.

The GDOP depends on the geometry of the satellites in relation to the user's receiver. It is independent of the quality of the broadcast signals and the user's receiver. Generally speaking, the GDOP measures the "spread" of the satellites around the receiver. The optimum case would be to have one satellite directly overhead and the other three spaced 120° around the receiver on the horizon. The worst GDOP would occur if the satellites were spaced closely together or in a line overhead.

There are special types of DOP's for each of the posi-

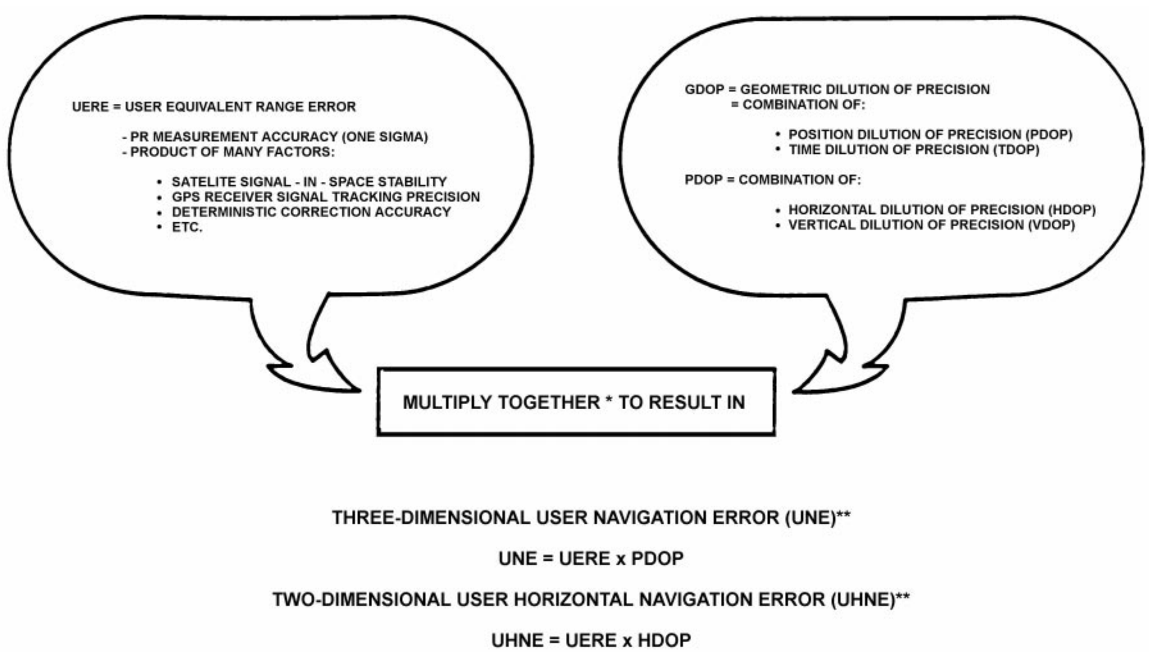


Figure 1110. Position and time error computations.

tion and time solution dimensions; these particular DOP's combine to determine the GDOP. For the vertical dimension, the **vertical dilution of precision (VDOP)** describes the effect of satellite geometry on altitude calculations. The **horizontal dilution of precision (HDOP)** describes satellite geometry's effect on position (latitude and longitude) errors. These two DOP's combine to determine the **position dilution of precision (PDOP)**. The PDOP combined with the **time dilution of precision (TDOP)** results in the GDOP. See Figure 1110.

1111. Ionospheric Delay Errors

Section 1107 covered errors in GPS positions due to errors inherent in the satellite signal (UERE) and the geometry of the satellite constellation (GDOP). Another major cause of accuracy degradation is the effect of the ionosphere on the radio frequency signals that comprise the GPS signal.

A discussion of a model of the earth's atmosphere will be useful in understanding this concept. Consider the earth as surrounded by three layers of atmosphere. The first layer, extending from the surface of the earth to an altitude of approximately 10 km, is known as the troposphere. Above the troposphere and extending to an altitude of approximately 50 km is the stratosphere. Finally, above the stratosphere and extending to an altitude that varies as a function of the time of day is the **ionosphere**. Though radio signals are subjected to effects which degrade its accuracy in all three layers of this atmospheric model, the effects of the ionosphere are the most significant; therefore, they will be discussed here.

The ionosphere, as the name implies, is that region of the atmosphere which contains a large number of ionized molecules and a correspondingly high number of free electrons. These charged molecules are those which have lost one or more electrons. No atom will loose an electron without an input of energy; the energy input that causes the ions to be formed in the ionosphere comes from the ultraviolet (U-V) radiation of the sun. Therefore, the more intense the sun's rays, the larger the number of free electrons which will exist in this region of the atmosphere.

The largest effect that this ionospheric effect has on GPS accuracy is a phenomenon known as **group time delay**. As the name implies, group time delay results in a delay in the time a signal takes to travel through a given distance. Obviously, since GPS relies on extremely accurate timing measurement of these signals between satellites and ground receivers, this group time delay can have a noticeable effect on the magnitude of GPS position error.

The group time delay is a function of several elements. It is inversely proportional to the square of the frequency at which the satellite transmits, and it is directly proportional to the atmosphere's **total electron content (TEC)**, a measure of the degree of the atmosphere's ionization. The general form of the equation describing the delay effect is:

$$\Delta t = \frac{(K \times TEC)}{f^2}$$

where

Δt = group time delay
f = operating frequency
K = constant

Since the sun's U-V radiation ionizes the molecules in the upper atmosphere, it stands to reason that the time delay value will be highest when the sun is shining and lowest at night. Experimental evidence has borne this out, showing that the value for TEC is highest around 1500 local time and lowest around 0500 local time. Therefore, the magnitude of the accuracy degradation caused by this effect will be highest during daylight operations. In addition to these daily variations, the magnitude of this time delay error also varies with the seasons; it is highest at the vernal equinox. Finally, this effect shows a solar cycle dependence. The greater the number of sunspots, the higher the TEC value and the greater the group time delay effect. The solar cycle typically follows an eleven year pattern. Solar cycle 22 began in 1986, peaked in 1991, and is now in decline. It should reach a minimum in 1997, at which time the effect on the group time delay from this phenomenon will also reach a minimum.

Given that this ionospheric delay introduces a serious accuracy degradation into the system, how does GPS account for it? There are two methods used: (1) the dual frequency technique, and (2) the ionospheric delay method.

1112. Dual Frequency Correction Technique

As the term implies, the dual frequency technique requires the ability to acquire and track both the L1 and L2 frequency signals. Recall from the discussion in section 1105 that the C/A and P codes are transmitted on carrier frequency L1, but only the P code is transmitted on L2. Recall also from section 1105 that only authorized operators with access to DOD cryptographic material are able to copy the P code. It follows, then, that only those authorized users are able to copy the L2 carrier frequency. Therefore, only those authorized users are able to use the dual frequency correction method. The dual frequency method measures the distance between the satellite and the user based on both the L1 and L2 carrier signal. These ranges will be different because the group time delay for each signal will be different. This is because of the frequency dependence of the time delay error. The range from the satellite to the user will be the true range combined with the range error caused by the time delay, as shown by the following equation:

$$R(f) = R_{actual} + \text{error term}$$

where R(f) is the range which differs from the actual range as a function of the carrier frequency. The dual frequency correction method takes two such range measurements, R(L1) and R(L2). Recall that the error term is a function of a constant divided by the square of the frequency. By combining the two range equations derived from the two frequency measurements, the constant term can be eliminated and one is left with an equation in which the true range is simply a function of the two carrier frequencies and the measured ranges R(L1) and R(L2). This method has two major advantages over the ionospheric model method. (1) It calculates corrections from real-time measured data; therefore, it is more accurate. (2) It alleviates the need to include ionospheric data on the navigation message. A significant portion of the data message is devoted to ionospheric correction data. If the receiver is dual frequency capable, then it does not need any of this data.

The vast majority of maritime users cannot copy dual frequency signals. For them, the ionospheric delay model provides the correction for the group time delay.

1113. The Ionospheric Delay Model

The ionospheric delay model mathematically models the diurnal ionospheric variation. The value for this time delay is determined from a cosinusoidal function into which coefficients representing the maximum value of the time delay (i.e., the amplitude of the cosine wave representing the delay function); the time of day; the period of the variation; and a minimum value of delay are introduced. This model is designed to be most accurate at the diurnal maximum. This is obviously a reasonable design consideration because it is at the time of day when the maximum diurnal time delay occurs that the largest magnitude of error appears. The coefficients for use in this delay model are transmitted to the receiver in the navigation data message. As stated in section 1112, this method of correction is not as accurate as the dual frequency method; however, for the non-military user, it is the only method of correction available.

1114. Multipath Reflection Errors

Multipath reflection errors occur when the receiver detects parts of the same signal at two different times. The first reception is the direct path reception, the signal that is received directly from the satellite. The second reception is from a reflection of that same signal from the ground or any other reflective surface. The direct path signal arrives first, the reflected signal, having had to travel a longer distance to the receiver, arrives later. The GPS signal is designed to minimize this multipath error. The L1 and L2 frequencies used demonstrate a diffuse reflection pattern, lowering the signal strength or any reflection that arrives at the receiver. In addition, the receiver's antenna can be designed to reject a signal that it recognizes as a reflection. In addition to the properties of the carrier frequencies, the high data frequency of both the P and C/A codes and their resulting good correlation properties minimize the effect of multipath propagation.

The design features mentioned above combine to reduce the maximum error expected from multipath propagation to less than 20 feet.

DIFFERENTIAL GPS

1115. Differential GPS Concept

The discussions above make it clear that the Global Positioning System provides the most accurate positions available to navigators today. They should also make clear that the most accurate positioning information is available to only a small fraction of the using population: U.S. and allied military. For most open ocean navigation applications, the degraded accuracy inherent in selective availability and the inability to copy the precision code presents no serious hazard to navigation. A mariner seldom if ever needs greater than 100 meter accuracy in the middle of the ocean.

It is a different situation as the mariner approaches shore. Typically for harbor approaches and piloting, the mariner will shift to visual piloting. The increase in accuracy provided by this navigational method is required to ensure ship's safety. The 100 meter accuracy of GPS in this situation is not sufficient. Any mariner who has groped his way through a restricted channel, in a fog obscuring all visual navigation aids will certainly appreciate the fact that even a degraded GPS position is available for them to plot. However, 100 meter accuracy is not sufficient to ensure ship's safety in most piloting situations. In this situation, the mariner needs P code accuracy. The problem then becomes how to obtain the accuracy of the Precise Positioning Service with due regard to the legitimate security concerns of the U.S. military. The answer to this seeming dilemma lies in the concept of **Differential GPS (DGPS)**.

Differential GPS is a system in which a receiver at an accurately surveyed position utilizes GPS signals to calculate timing errors and then broadcasts a correction signal to account for these errors. This is an extremely powerful concept. The errors which contribute to GPS accuracy degradation, ionospheric time delay and selective availability, are experienced simultaneously by both the DGPS receiver and a relatively close user's receiver. The extremely high altitude of the GPS satellites means that, as long as the DGPS receiver is within 100-200 km of the user's receiver, the user's receiver is close enough to take advantage of any DGPS correction signal.

The theory behind a DGPS system is straightforward. Located on an accurately surveyed site, the DGPS receiv-

er already knows its location. It receives data which tell it where the satellite is. Knowing the two locations, it then calculates the time it should take for a satellite's signal to reach it. It compares the time that it *actually* takes for the signal to arrive. This difference in time between the theoretical and the actual is the basis for the DGPS receiver's computation of a timing error signal; this difference in time is caused by all the errors to which the GPS signal is subjected; errors, except for receiver error and multipath error, to which both the DGPS and the user's receivers are simultaneously subject. The DGPS system then broadcasts a timing correction signal, the effect of which is to correct for selective availability, ionospheric delay, and all the other error sources the two receivers share in common.

For suitably equipped users, DGPS results in positions as accurate as if not more accurate than those obtainable by the Precise Positioning Service. For the mariner approaching a harbor or piloting in restricted waters near a site with a DGPS transmitter, the accuracy required for ship's safety is now available from a system other than plotting visual bearings. This capability is not limited to simply displaying the correct position for the navigator to plot. The DGPS position can be used as the prime input to an electronic chart system, providing an electronic readout of position accurate enough to pilot safely in the most restricted channel. The U.S. Coast Guard presently plans to install DGPS systems to provide 100% coverage along the eastern seaboard, the Gulf Coast, and the Pacific coast. Alaska and Hawaii will also be covered with a DGPS network. The DGPS signal will be broadcast using existing radiobeacons.

DGPS accuracy will revolutionize marine navigation. It is important to note, however, that, even with the development of the electronic chart and the proliferation of accurate, real-time electronic navigation systems, the mariner should not let his skills in the more traditional areas of navigation, such as celestial navigation and piloting, wane. They will become important secondary methods; any mariner who has put his faith in electronic navigation only to see the system suffer an electronic failure at sea can attest to the importance of maintaining proficiency in the more traditional methods of navigation. However, there is no doubt that the ease, convenience, and accuracy of DGPS will revolutionize the practice of marine navigation.

CHAPTER 12

HYPERBOLIC SYSTEMS

INTRODUCTION TO LORAN C

1200. History

The theory behind the operation of hyperbolic radionavigation systems was known in the late 1930's, but it took the urgency of World War II to speed development of the system into practical use. By early 1942, the British had an operating hyperbolic system in use designed to aid in long range bomber navigation. This system, named Gee, operated on frequencies between 30 MHz and 80 MHz and employed master and "slave" transmitters spaced approximately 100 miles apart. The Americans were not far behind the British in development of their own system. By 1943, the U. S. Coast Guard was operating a chain of hyperbolic navigation transmitters that became Loran A. By the end of the war, the network consisted of over 70 transmitters covering over 30% of the earth's surface.

In the late 1940's and early 1950's, experiments in low frequency Loran produced a longer range, more accurate system. Using the 90-110 kHz band, Loran developed into a 24-hour-a-day, all-weather radionavigation system. Serving both the marine and aviation communities, Loran C boasts the highest number of users of any precise radionavigation system in use. It has been designated the primary federally provided marine navigation system for the U. S. Coastal Confluence Zone (CCZ), southern Alaska, and the Great Lakes. The maritime community comprises the vast majority of Loran C users (87%), followed by civil aviation users (14%). The number of Loran users is projected to grow until well into the next century.

Notwithstanding the popularity of the system, the U. S. Department of Defense is phasing out use of Loran C in favor of the highly accurate, space-based Global Positioning System (GPS). This phase out has resulted in closing the Hawaii-based Central Pacific Loran C chain and transferring several overseas Loran C stations to host governments. The use of Loran C in the United States' radionavigation plan will undergo continuous evaluation until a final determination of the future of the system is made in 1996. At that point, a decision will be made to either continue operations or to begin to phase out the system in favor of satellite navigation. No matter what decision is reached, Loran C is expected to remain operational until at least 2015.

LORAN C DESCRIPTION

1201. Basic Theory Of Operation

The Loran C system consists of a chain of transmitting stations, each separated by several hundred miles. Within the Loran chain, one station is designated as the **master station** and the others as **secondary stations**. There must be at least two secondary stations for one master station; therefore, every Loran transmitting chain will contain at least three transmitting stations. The master and secondary stations transmit radio pulses at precise time intervals. A Loran receiver measures the **time difference** (TD) in reception at the vessel between these pulses; it then displays either this difference or a computed latitude and longitude to the operator.

The signal arrival time difference between a given master-secondary pair corresponds to the difference in distance between the receiving vessel and the two stations. The locus of points having the same time difference from a specific master-secondary pair forms a hyperbolic line of position (LOP). The intersection of two or more of these LOP's produces a fix of the vessel's position.

There are two methods by which the navigator can convert these time differences to geographic positions. The first involves the use of a chart overprinted with a Loran **time delay lattice** consisting of time delay lines spaced at convenient intervals. The navigator plots the displayed time difference by interpolating between the lattice lines printed on the chart. In the second method computer algorithms in the receiver's software convert the time delay signals to latitude and longitude for display.

Early receiver conversion algorithms were imprecise; however, modern receivers employ more precise algorithms. Their position output is usually well within the 0. 25 NM accuracy specification for Loran C. Modern receivers can also navigate by employing waypoints, directing a vessel's course between two operator-selected points. Section 1207, section 1208, and section 1209 more fully explore questions of system employment.

1202. Components Of The Loran System

The components of the Loran system consist of the land-

based **transmitting stations**, the Loran **receiver** and **antenna**, and the **Loran charts**. Land-based facilities include master transmitting stations, at least two secondary transmitters for each master transmitter, control stations, monitor sites, and a time reference. The transmitters transmit the Loran signals at precise intervals in time. The control station and associated monitor sites continually measure the characteristics of the Loran signals received to detect any anomalies or any out-of-specification condition. Some transmitters serve only one function within a chain (i.e., either master or secondary); however, in several instances, one transmitter can serve as the master of one chain and secondary in another. This dual function lowers the overall costs and operating expense for the system.

Loran receivers exhibit varying degrees of sophistication; however, their signal processing is similar. The first processing stage consists of **search and acquisition**, during which the receiver searches for the signal from a particular Loran chain, establishing the approximate location in time of the master and secondaries with sufficient accuracy to permit subsequent settling and tracking.

After search and acquisition, the receiver enters the **settling phase**. In this phase, the receiver searches for and detects the front edge of the Loran pulse. After detecting the front edge of the pulse, it selects the correct cycle of the pulse to track.

Having selected the correct tracking cycle, the receiver begins the **tracking and lock** phase, in which the receiver maintains synchronization with the selected received signals. Once this phase is reached, the receiver displays either the time difference of the signals or the computed latitude and longitude as discussed above.

1203. Description Of Operation

The Loran signal consists of a series of 100 kHz pulses sent first by the master station and then, in turn, by the secondary stations. For the master signal, a series of nine pulses is transmitted, the first eight spaced 1000 μsec apart followed by a ninth transmitted 2000 μsec after the eighth. Pulsed transmission results in lower power output requirements, better signal identification properties, and more precise timing of the signals. After the time delays discussed below, secondary stations transmit a series of eight pulses, each spaced 1000 μsec apart. The master and secondary stations in a chain transmit at precisely determined intervals. First, the master station transmits; then, after a specified interval, the first secondary station transmits. Then the second secondary transmits, and so on. Secondary stations are given letter designations of W, X, Y, and Z; this letter designation indicates the order in which they transmit following the master. When the master signal reaches the next secondary in sequence, this secondary station waits an interval, defined as the **secondary coding delay, (SCD)** or simply **coding delay (CD)**, and then transmits. The total elapsed time from the master transmission until the secondary emission is termed the **emissions delay (ED)**. The ED is the sum of the time for the master signal to travel to the secondary and the CD. The time required for the master to travel to the secondary is defined as the **baseline travel time (BTT)** or **baseline length (BLL)**. After the first secondary transmits, the remaining secondaries transmit in order. Each of these secondaries has its own CD/ED value. Once the last secondary has transmitted, the master transmits again, and the cycle is repeated. The time to complete this cycle of transmission defines an important characteristic for the chain: the **group repetition interval (GRI)**. The group repetition interval divided by ten yields the chain's designator. For example, the interval between successive transmissions of the master pulse group for the northeast US chain is 99,600 μsec. From the definition above, the GRI designator for this chain is defined as 9960. The GRI must be sufficiently large to allow the signals from the master and secondary stations in the chain to propagate fully throughout the region covered by the chain before the next cycle of pulses begins.

Other concepts important to the understanding of the operation of Loran are the baseline and baseline extension. The geographic line connecting a master to a particular secondary station is defined as the station pair **baseline**. The baseline is, in other words, that part of a great circle on which lie all the points connecting the two stations. The extension of this line beyond the stations to encompass the points along this great circle not lying between the two stations defines the **baseline extension**. The importance of these two concepts will become apparent during the discussion of Loran accuracy considerations below.

As discussed above, Loran C relies on time differences between two or more received signals to develop LOP's used to fix the ship's position. This section will examine in greater detail the process by which the signals are developed, transmitted, and ultimately interpreted by the navigator.

The basic theory behind the operation of a hyperbolic system is straightforward. First, the locus of points defining a constant difference in distance between a vessel and two separate stations is described by a mathematical function that, when plotted in two dimensional space, yields a hyperbola. Second, assuming a constant speed of propagation of electromagnetic radiation in the atmosphere, the time difference in the arrival of electromagnetic radiation from the two transmitter sites to the vessel is proportional to the distance between the transmitting sites and the vessel. The following equations demonstrating this proportionality between distance and time apply:

Distance=Velocity x Time

or, using algebraic symbols

$d = c \times t$

Therefore, if the velocity (c) is constant, the distance between a vessel and two transmitting stations will be directly proportional to the time delay detected at the vessel

between pulses of electromagnetic radiation transmitted from the two stations.

An example will better illustrate the concept. See Figure 1203a. Assume that two Loran transmitting stations, a master and a secondary, are located along with an observer in a Cartesian coordinate system whose units are in nautical miles. Assume further that the master station is located at coordinates (x,y) = (-200,0) and the secondary is located at (x,y) = (+200,0). Designate this secondary station as station Xray. An observer with a receiver capable of detecting electromagnetic radiation is positioned at any point A whose coordinates are defined as $x_{(a)}$ and $y_{(a)}$. The Pythagorean theorem can be used to determine the distance between the observer and the master station; similarly, one can obtain the distance between the observer and the secondary station. This methodology yields the following result for the given example:

$$distance_{am} = [x_a + 200^2 + y_a^2]^{0.5}$$

$$distance_{as} = [(x_a - 200)^2 + y_a^2]^{0.5}$$

Finally, the difference between these distances (Z) is given by the following:

$$Z = d_{am} - d_{as}$$

After algebraic manipulation,

$$Z = [(x_a + 200)^2 + y_a^2]^{0.5} - [(x_a - 200)^2 + y_a^2]^{0.5}$$

With a given position of the master and secondary stations, therefore, the function describing the difference in distance is reduced to one variable; i.e., the position of the observer.

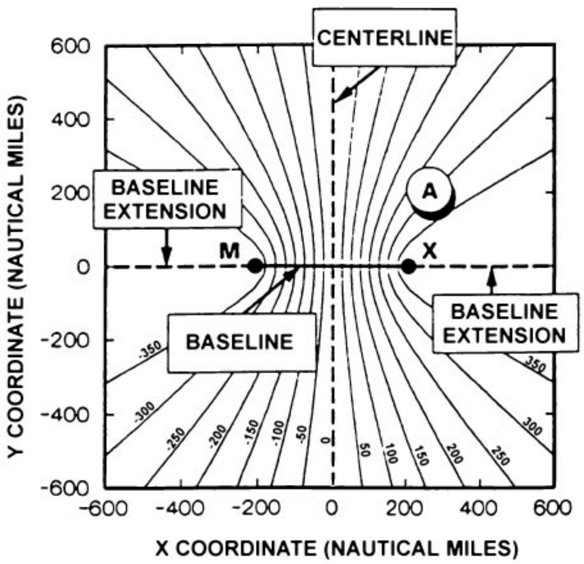


Figure 1203a. Depiction of Loran LOP's.

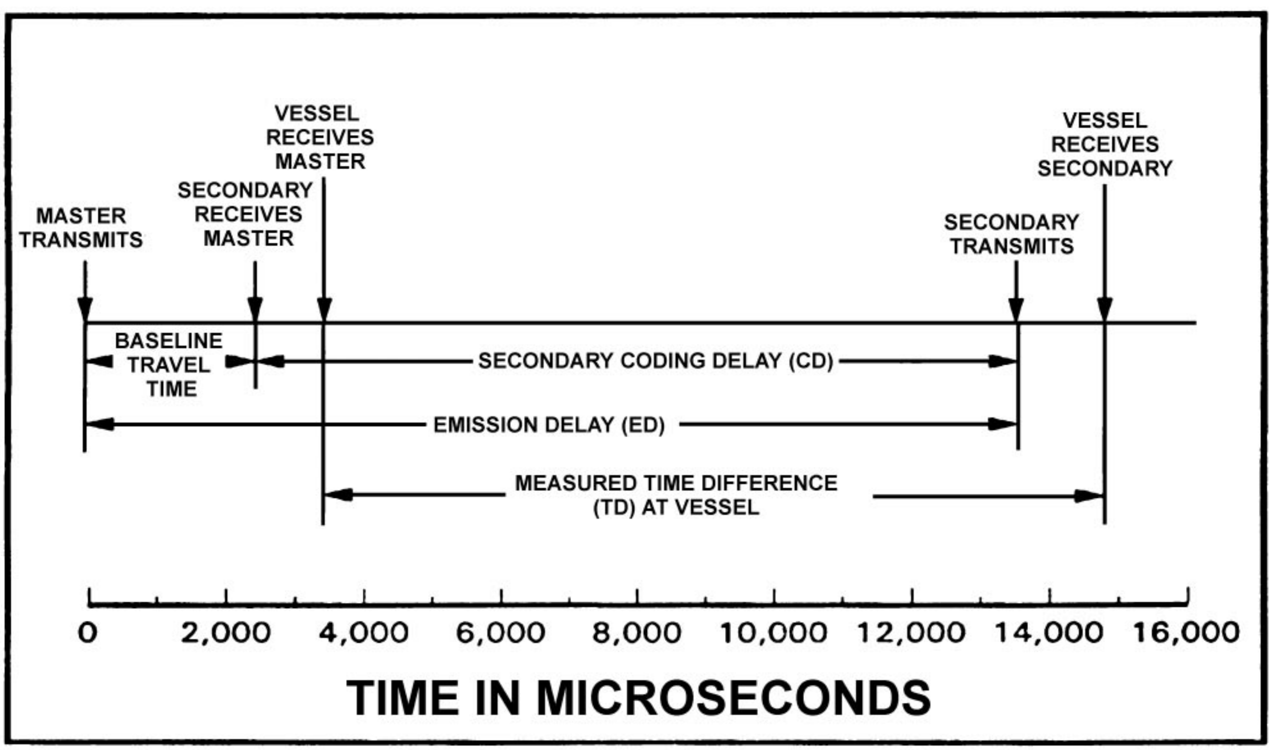


Figure 1203b. The time axis for Loran C TD for point "A."

Figure 1203a is a conventional graphical representation of the data obtained from solving for the value (Z) using varying positions of A in the example above. The hyperbolic lines of position in the figure represent the locus of points along which the observer's simultaneous distances from the master and secondary stations are equal; he is on the centerline. For example, if the observer above were located at the point (271. 9, 200) then the distance between that observer and the secondary station (in this case, designated "X") would be 212. 5 NM. In turn, the observer's distance from the master station would be 512. 5 nautical miles. The function Z would simply be the difference of the two, or 300 NM. Refer again to Figure 1203a. The hyperbola marked by "300" represents the locus of points along which the observer is simultaneously 300 NM closer to the secondary transmitter than to the master. To fix his position, the observer must obtain a similar hyperbolic line of position generated by another master-secondary pair. Once this is done, the intersection of the two LOP's can be determined, and the observer can fix his position in the plane at a discrete position in time.

The above example was evaluated in terms of differences in distance; as discussed previously, an analogous situation exists with respect to differences in signal reception time. All that is required is the assumption that the signal propagates at constant speed. Once this assumption is made, the hyperbolic LOP's in Figure 1203a above can be re-labeled to indicate time differences instead of distances. This principle is graphically demonstrated in Figure 1203b.

Assume that electromagnetic radiation travels at the speed of light (one nautical mile traveled in 6. 18 μsec) and reconsider point A from the example above. The distance from the master station to point A was 512. 5 NM. From the relationship between distance and time defined above, it would take a signal (6.18 μsec/NM) × 512. 5 NM = 3,167 μsec to travel from the master station to the observer at point A. At the arrival of this signal, the observer's Loran receiver would start the time delay (TD) measurement. Recall from the general discussion above that a secondary station transmits after an emissions delay equal to the sum of the baseline travel time and the secondary coding delay. In this example, the master and the secondary are 400 NM apart; therefore, the baseline travel time is (6.18 μsec/NM) × 400 NM = 2,472 μsec. Assuming a secondary coding delay of 11,000 μsec, the secondary station in this example would transmit (2,472 + 11,000)μsec or 13,472 μsec after the master station. The signal must then reach the receiver located with the observer at point A. Recall from above that this distance was 212. 5 NM. Therefore, the time associated with signal travel is: (6. 18 μsec/NM) × 212. 5 NM = 1,313 μsec. Therefore, the total time from transmission of the master signal to the reception of the secondary signal by the observer at point A is (13,472 + 1,313) μsec = 14,785 μsec.

Recall, however, that the Loran receiver measures the time delay between reception of the master signal and the reception of the secondary signal. The quantity determined above was the total time from the transmission of the master signal to the reception of the secondary signal. Therefore, the time quantity above must be corrected by subtracting the amount of time required for the signal to travel from the master transmitter to the observer at point A. This amount of time was 3,167 μsec. Therefore, the time delay observed at point A in this hypothetical example is (14,785 - 3,167) μsec or 11,618 μsec. Once again, this time delay is a function of the simultaneous differences in distance between the observer and the two transmitting stations, and it gives rise to a hyperbolic line of position which can be crossed with another LOP to fix the observer's position at a discrete position.

1204. Allowances For Non-Uniform Propagation Rates

The proportionality of the time and distance differences assumes a constant speed of propagation of electromagnetic radiation. To a first approximation, this is a valid assumption; however, in practice, Loran's accuracy criteria require a refinement of this approximation. The initial calculations above assumed the speed of light in a vacuum; however, the actual speed at which electromagnetic radiation propagates through the atmosphere is affected by both the medium through which it travels and the terrain over which it passes. The first of these concerns, the nature of the atmosphere through which the signal passes, gives rise to the first correction term: the **Primary Phase Factor (PF)**. This correction is transparent to the operator of a Loran system because it is incorporated into the charts and receivers used with the system, and it requires no operator action.

A **Secondary Phase Factor (SF)** accounts for the effect traveling over seawater has on the propagated signal. This correction, like the primary phase factor above, is transparent to the operator since it is incorporated into charts and system receivers.

The third and final correction required because of non-uniform speed of electromagnetic radiation is termed the **Additional Secondary Phase Factor (ASF)**. Of the three corrections mentioned in this section, this is the most important one to understand because its correct application is crucial to obtaining the most accurate results from the system. This correction is required because the SF described above assumes that the signal travels only over water when the signal travels over terrain composed of water and land. The ASF can be determined from either a mathematical model or a table constructed from empirical measurement. The latter method tends to yield more accurate results. To complicate matters further, the ASF varies seasonally.

The ASF correction is important because it is required to convert Loran time delay measurements into geographic coordinates. ASF corrections must be used with care. Some Loran charts incorporate ASF corrections while others do not. One cannot manually apply ASF correction to measured time delays when using a chart that has already been corrected. In addition, the accuracy of ASF's is much less accurate within 10 NM of the coastline. Therefore, navigators must use prudence and caution when operating with

ASF corrections in this area.

One other point must be made about ASF corrections. Some commercially available Loran receivers contain preprogrammed ASF corrections for the conversion of measured time delays into latitude and longitude printouts. The internal values for ASF corrections used by these receivers may or may not be accurate, thus leading to the possibility of navigational error. Periodically, the navigator should compare his receiver's latitude and longitude readout with either a position plotted on a chart incorporating ASF corrections for observed TD's or a position determined from manual TD correction using official ASF published values. This procedure can act as a check on his receiver's ASF correction accuracy. When the navigator wants to take full advantage of the navigational accuracy of the Loran system, he should use and plot the TD's generated by the receiver, not the converted latitude and longitude. When precision navigation is not required, converted latitude and longitude may be used.

1205. Loran Pulse Architecture

As mentioned above, Loran uses a pulsed signal rather than a continuous wave signal. This section will analyze the Loran pulse signal architecture, emphasizing design and operational considerations.

Figure 1205 represents the Loran signal. Nine of these signals are transmitted by the master station and eight are transmitted by the secondary stations every transmission cycle. The pulse exhibits a steep rise to its maximum ampli-

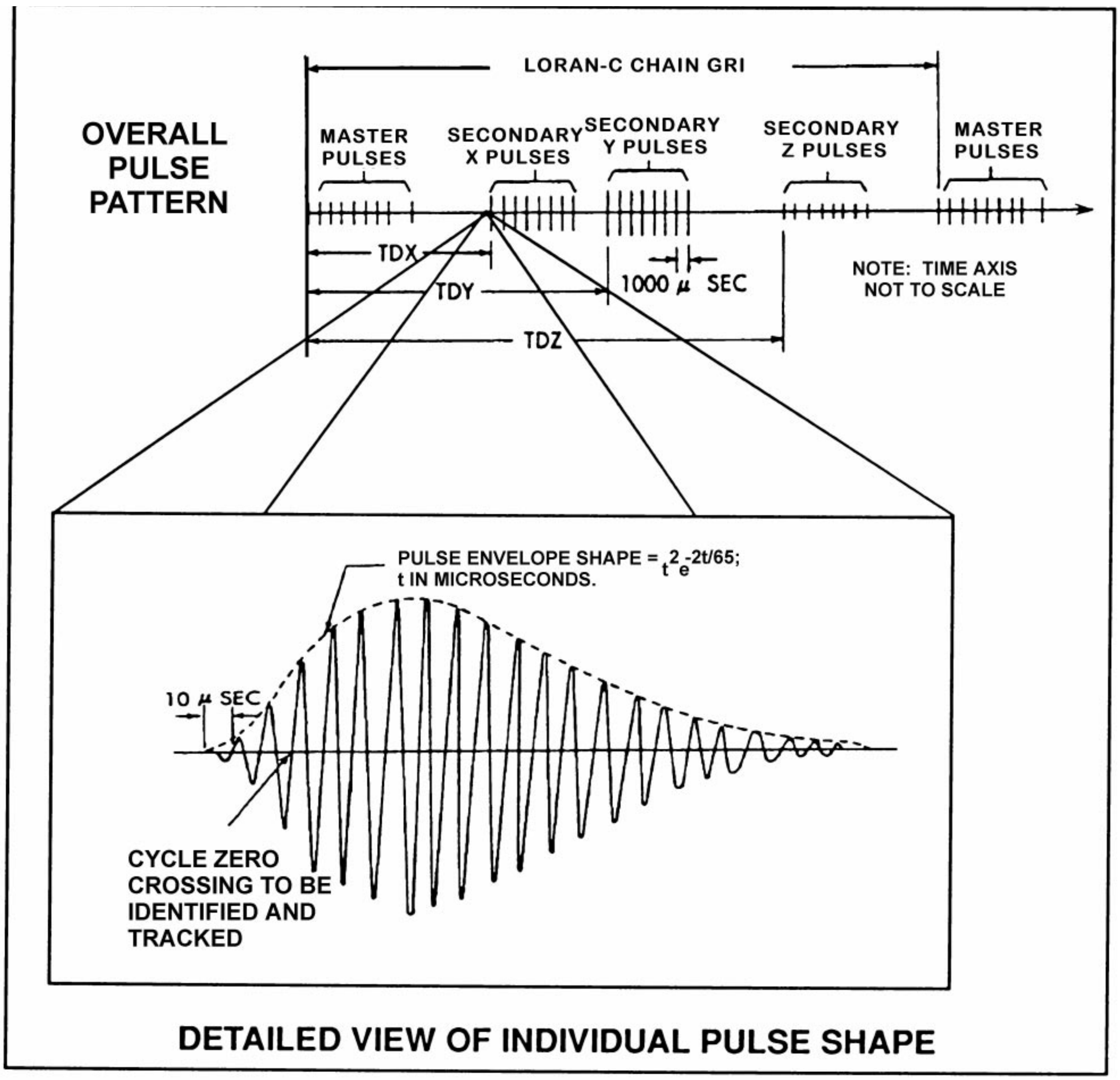


Figure 1205. Pulse pattern and shape for Loran C transmission.

tude within 65 μsec of emission and an exponential decay to zero within 200 to 300 μsec. The signal frequency is nominally defined as 100 kHz; in actuality, the signal is designed such that 99% of the radiated power is contained in a 20 kHz band centered on 100 kHz.

The Loran receiver is programmed to detect the signal on the cycle corresponding to the carrier frequency's third positive crossing of the x axis. This occurrence, termed the **third positive zero crossing**, is chosen for two reasons. First, it is late enough for the pulse to have built up sufficient signal strength for the receiver to detect it. Secondly, it is early enough in the pulse to ensure that the receiver is detecting the transmitting station's ground wave pulse and not its sky wave pulse. Sky wave pulses are affected by atmospheric refraction and induce large errors into positions determined by the Loran system. Pulse architecture is designed to eliminate this major source of error.

Another pulse feature designed to eliminate sky wave contamination is known as **phase coding**. With phase coding, the phase of the carrier signal (i.e. , the 100 kHz signal) is changed systematically from pulse to pulse. Upon reaching the receiver, sky waves will be out of phase with the simultaneously received ground waves and, thus, they will not be recognized by the receiver. Although this phase coding offers several technical advantages, the one most important to the operator is this increase in accuracy due to the rejection of sky wave signals.

The final aspect of pulse architecture that is important to the operator is **blink coding**. When a signal from a secondary station is unreliable and should not be used for navigation, the affected secondary station will blink; that is, the first two pulses of the affected secondary station are turned off for 3. 6 seconds and on for 0. 4 seconds. This blink is detected by the Loran receiver and displayed to the operator. When the blink indication is received, the operator should not use the affected secondary station.

LORAN C ACCURACY CONSIDERATIONS

1206. Position Uncertainty With Loran C

As discussed above, the TD's from a given master-secondary pair form a family of hyperbolae. Each hyperbola in this family can be considered a line of position; the vessel must be somewhere along that locus of points which form the hyperbola. A typical family of hyperbolae is shown in Figure 1206a.

Now, suppose the hyperbolic family from the master-Xray station pair shown in Figure 1203a were superimposed upon the family shown in Figure 1206a. The results would be the hyperbolic lattice shown in Figure 1206b.

Loran C LOP's for various chains and secondaries (the hyperbolic lattice formed by the families of hyperbolae for several master-secondary pairs) are printed on special nautical charts. Each of the sets of LOP's is given a separate color and is denoted by a characteristic set of symbols. For example, an LOP might be designated 9960-X-25750. The designation is read as follows: the chain GRI designator is 9960, the TD is for the Master-Xray pair (M-X), and the time difference along this LOP is 25750 μsec. The chart only shows a limited number of LOP's to reduce clutter on the chart. Therefore, if the observed time delay falls between two

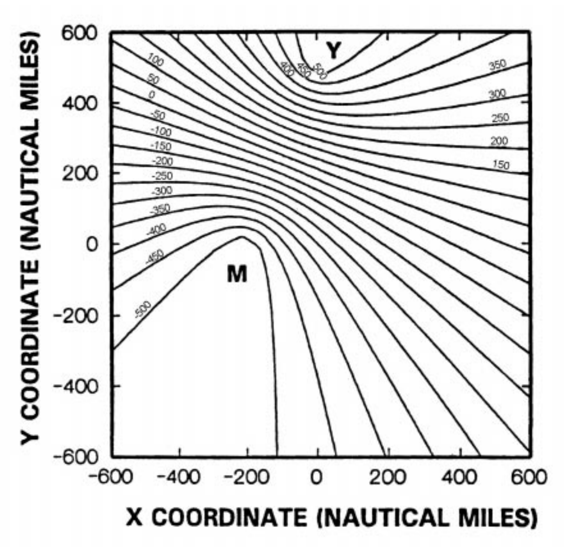


Figure 1206a. A family of hyperbolic lines generated by Loran signals.

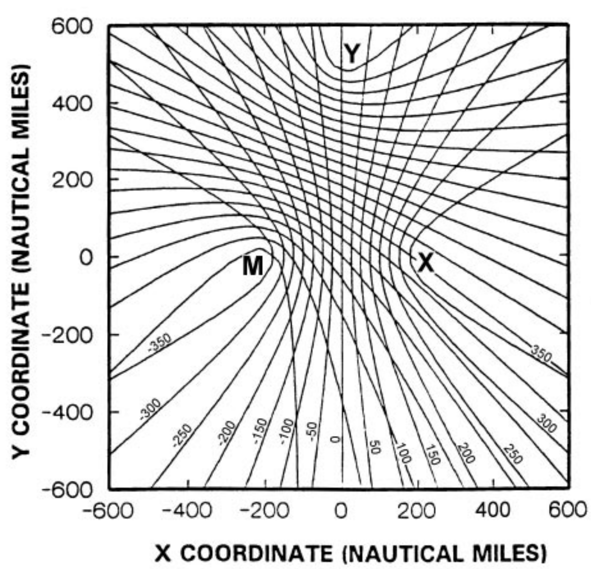


Figure 1206b. A hyperbolic lattice formed by station pairs M-X and M-Y.

charted LOP's, interpolate between them to obtain the precise LOP. After having interpolated (if necessary) between two TD measurements and plotted the resulting LOP's on the chart, the navigator marks the intersection of the LOP's and labels that intersection as his Loran fix.

A closer examination of Figure 1206b reveals two possible sources of Loran fix error. The first of these errors is a function of the LOP crossing angle. The second is a phenomenon known as fix ambiguity. Let us examine both of these in turn.

Figure 1206c shows graphically how error magnitude varies as a function of crossing angle. Assume that LOP 1 is known to contain no error, while LOP 2 has an uncertainly as shown. As the crossing angle (i.e. , the angle of intersection of the two LOP's) approaches 90°, range of possible positions along LOP 1 (i.e., the position uncertainty or fix error) approaches a minimum; conversely, as the crossing angle decreases, the position uncertainty increases; the line defining the range of uncertainty grows longer. This illustration demonstrates the desirability of choosing LOP's for which the crossing angle is as close to 90° as possible. The relationship between crossing angle and accuracy can be expressed mathematically:

$$\sin x = \frac{\text{LOP error}}{\text{fix uncertainty}}$$

where x is the crossing angle. Rearranging algebraically,

$$\text{fix uncertainty} = \frac{\text{LOP error}}{\sin x}.$$

Assuming that LOP error is constant, then position uncertainty is inversely proportional to the sine of the crossing angle. As the crossing angle increases from 0° to 90°, the sin of the crossing angle increases from 0 to 1. Therefore, the error is at a minimum when the crossing angle is 90°, and it increases thereafter as the crossing angle decreases.

Fix ambiguity can also cause the navigator to plot an erroneous position. Fix ambiguity results when one Loran LOP crosses another LOP in two separate places. Most Loran receivers have an ambiguity alarm to alert the navigator to this occurrence. Absent other information, the navigator is unsure as to which intersection marks his true position. Again, refer to Figure 1206b for an example. The -350 difference line from the master-Xray station pair crosses the -500 difference line from the master-Yankee station pair in two separate places. Absent a third LOP from either another station pair or a separate source, the navigator would not know which of these LOP intersections marked his position.

Fix ambiguity occurs in the area known as the master-secondary baseline extension, defined above in section 1203. Therefore, do not use a master-secondary pair while operating in the vicinity of that pair's baseline extension if other station pairs are available.

The large gradient of the LOP when operating in the vi-

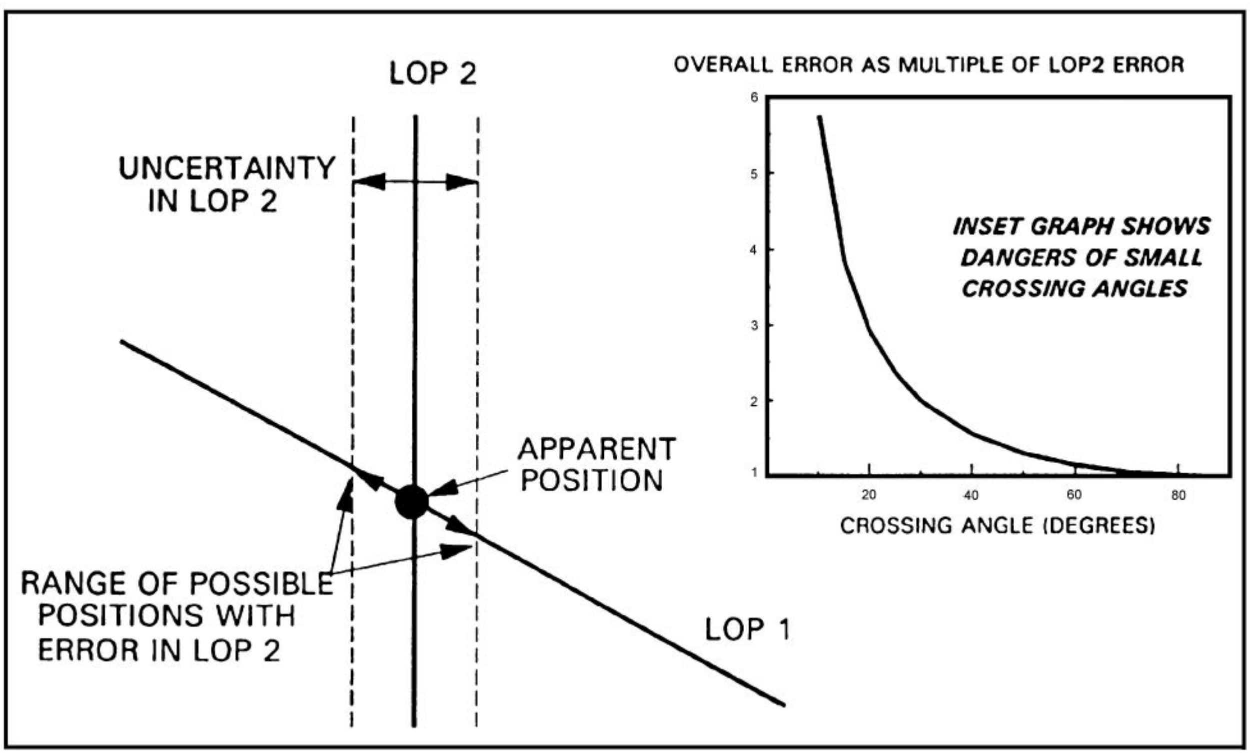


Figure 1206c. Error in Loran LOP's is magnified if the crossing angle is less than 90°.

cinity of a baseline extension is another reason to avoid using stations in the vicinity of their baseline extensions. Uncertainty error is directly proportional to the gradient of the LOP's used to determine the fix. Therefore, to minimize possible error, the gradient of the LOP's used should be as small as possible. Refer again to Figure 1206b. Note that the gradient is at a minimum along the station pair baseline and increases to its maximum value in the vicinity of the baseline extension.

The navigator, therefore, has several factors to consider in maximizing fix accuracy. Do not use a station pair when operating along it baseline extension because both the LOP gradient and crossing angle are unfavorable. In addition, fix ambiguity is more likely here.

LORAN C OPERATIONS

1207. Waypoint Navigation

A Loran receiver's major advantage is its ability to accept and store waypoints. Waypoints are sets of coordinates that describe a location of navigational interest. A navigator can enter waypoints into a receiver in one of two ways. He can either visit the area and press the appropriate receiver control key, or he can enter the waypoint coordinates manually. When manually entering the waypoint, he can express it either as a TD, a latitude and longitude, or a distance and bearing from another waypoint.

Typically, waypoints mark either points along a planned route or locations of interest. The navigator can plan his voyage as a series of waypoints, and the receiver will keep track of the vessel's progress in relation to the track between them. In keeping track of the vessel's progress, most receivers display the following parameters to the operator:

Cross Track Error (XTE): XTE is the perpendicular distance from the user's present position to the intended track between waypoints. Steering to maintain XTE near zero corrects for cross track current, cross track wind, and compass error.

Bearing (BRG): The BRG display, sometimes called the **Course to Steer** display, indicates the bearing from the vessel to the destination waypoint.

Distance to Go (DTG): The DTG display indicates the great circle distance between the vessel's present location and the destination waypoint.

Course and Speed Over Ground (COG and SOG): The COG and the SOG refer to motion over ground rather than motion relative to the water. Thus, COG and SOG reflect the combined effects of the vessel's progress through the water and the set and drift to which it is subject. The navigator may steer to maintain the COG equal to the intended track.

Loran navigation using waypoints was an important development because it showed the navigator his position *in relation to his intended destination*. Though this method of navigation is not a substitute for plotting a vessel's position on a chart to check for navigation hazards, it does give the navigator a second check on his plot.

1208. Using Loran's High Repeatable Accuracy

In discussing Loran employment, one must develop a working definition of three types of accuracy: **absolute accuracy**, **repeatable accuracy**, and **relative accuracy**. **Absolute accuracy** is the accuracy of a position with respect to the geographic coordinates of the earth. For example, if the navigator plots a position based on the Loran C latitude and longitude (or based on Loran C TD's) the difference between the Loran C position and the actual position is a measure of the system's absolute accuracy.

Repeatable accuracy is the accuracy with which the navigator can return to a position whose coordinates have been measured previously with the same navigational system. For example, suppose a navigator were to travel to a buoy and note the TD's at that position. Later, suppose the navigator, wanting to return to the buoy, returns to the previously-measured TD's. The resulting position difference between the vessel and the buoy is a measure of the system's repeatable accuracy.

Relative accuracy is the accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time. If one vessel were to travel to the TD's determined by another vessel, the difference in position between the two vessels would be a measure of the system's relative accuracy.

The distinction between absolute and repeatable accuracy is the most important one to understand. With the correct application of ASF's, the *absolute accuracy* of the Loran system varies from between 0. 1 and 0. 25 nautical miles. However, the *repeatable* accuracy of the system is much greater. If the navigator has been to an area previously and noted the TD's corresponding to different navigational aids (a buoy marking a harbor entrance, for example), the high repeatable accuracy of the system enables him to locate the buoy in under adverse weather. Similarly, selected TD data for various harbor navigational aids has been collected and recorded. These tables, if available to the navigator, provide an excellent backup navigational source to conventional harbor approach navigation. To maximize a Loran system's utility, exploit its high repeatable accuracy by using previously-determined TD measurements that locate positions critical to a vessel's safe passage. This statement raises an important question: Why use measured TD's and not a receiver's latitude and longitude output? If the navigator seeks to use the repeatable accuracy of the system, why does it matter if TD's or coordinates are used? The following section discusses this question.

1209. Time Delay Measurements And Repeatable Accuracy

The ASF conversion process is the reason for using TD’s and not Latitude/Longitude readings.

Recall that Loran receivers use ASF conversion factors to convert measured TD’s into coordinates. Recall also that the ASF corrections are a function of the terrain over which the signal must pass to reach the receiver. Therefore, the ASF corrections for one station pair are different from the ASF corrections for another station pair because the signals from the different pairs must travel over different terrain to reach the receiver. A Loran receiver does not always use the same pairs of stations to calculate a fix. Suppose a navigator marks the position of a channel buoy by recording its latitude and longitude as determine by his Loran receiver. If, on the return trip, the receiver tracks different station pairs, the latitude and longitude readings *for the exact same buoy* would be different because the new station pair would be using a different ASF correction. The same effect would occur if the navigator attempted to find the buoy with another receiver. By using previously-measured TD’s and not previously-measured latitudes and longitudes, this ASF introduced error is eliminated.

						9960-W							33W
						LONGITUDE WEST							
LATITUDE NORTH	75° 0'	55	50	45	40	35	30	25	20	15	10	5	74° 0'
39°0'				-0.9	-1.0	-0.9	-0.9	-0.8	-0.7	-0.6	-0.6	-0.6	-0.5
55	-1.4	-1.2	-1.1	-0.9	-0.9	-0.9	-0.8	-0.7	-0.7	-0.6	-0.6	-0.6	-0.5
50	-1.3	-1.1	-1.0	-0.9	-0.8	-0.8	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.5
45	-1.3	-1.0	-1.0	-0.9	-0.9	-0.7	-0.6	-0.7	-0.6	-0.6	-0.6	-0.6	-0.5
40	-1.3	-1.1	-1.0	-0.9	-0.8	-0.7	-0.6	-0.7	-0.7	-0.6	-0.6	-0.5	-0.6
35	-1.1	-1.0	-1.0	-0.9	-0.8	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
30	-1.0	-1.0	-1.0	-0.8	-0.7	-0.6	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6
25	-1.0	-1.1	-0.9	-0.8	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
20	-0.9	-0.9	-0.8	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
15	-0.8	-0.8	-0.8	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
10	-0.6	-0.6	-0.7	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
5	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
38°0'	-0.3	-0.6	-0.7	-0.7	-0.7	-.06	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
55	-0.4	-0.5	-0.6	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	
50	-0.3	-0.3	-0.6	-0.7	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6		
45	-0.3	-0.4	-0.6	-0.6	-0.6	-0.6	-0.7	-0.6	-0.6	-0.6	-0.6		
40	-0.3	-0.3	-0.4	-0.5	-0.6	-0.7	-0.7	-0.6	-0.6	-0.6			
35	-0.2	-0.3	-0.3	-0.5	-0.7	-0.6	-0.7	-0.6	-0.6				
30	-0.2	-0.2	-0.3	-0.4	-0.6	-0.6	-0.7	-0.6					
25	-0.2	-0.2	-0.3	-0.4	-0.6	-0.5	-0.7						
20	-0.2	-0.2	-0.3	-0.4	-0.6	-0.5	-0.6						
15	-0.2	-0.2	-0.3	-0.3	-0.5	-0.4	-0.6						
10	-0.2	-0.2	-0.2	-0.3	-0.4	-0.4							
5	-0.2	-0.3	-0.2	-0.3	-0.4	-0.4				Area Outside of CCZ			
37°0'	-0.2	-0.2	-0.2	-0.2	-0.4								
55	-0.2	-0.2	-0.2	-0.2	-0.3								
50	-0.2	-0.2	-0.2	-0.2	-0.2								
45	-0.2	-0.2	-0.2	-0.2									
40	-0.2	-0.2	-0.2	-0.2									
35	-0.2	-0.2	-0.2	-0.2									
30	-0.2	-0.2	-0.2	-0.1									
25	-0.2	-0.2	-0.2	-0.0									
20	-0.2	-0.2	-0.2	-0.0									
15	-0.2	-0.2	-0.1	-0.0	0.0								
10	-0.2	-0.1	-0.1	-0.0	0.0	0.1							
5	-0.1	-0.0	-0.0	-0.0	0.1	0.1							
36°0'	-0.1	-0.0	-0.0	-0.1	0.1	0.2	0.3						

Figure 1210. Excerpt from Loran C correction tables.

Envision the process this way. A receiver measures between measuring these TD's and displaying a latitude and longitude, the receiver accomplishes an intermediate step: applying the ASF corrections. This intermediate step is fraught with potential error. The accuracy of the corrections is a function of the stations received, the quality of the ASF correction software used, and the type of receiver employed. Measuring and using TD's eliminates this step, thus increasing the system's repeatable accuracy.

Many Loran receivers store waypoints as latitude and longitude coordinates regardless of the form in which the operator entered them into the receiver's memory. That is, the receiver applies ASF corrections prior to storing the waypoints. If, on the return visit, the same ASF's are applied to the same TD's, the latitude and longitude will also be the same. But a problem similar to the one discussed above will occur if different secondaries are used. Avoid this problem by recording all the TD's of waypoints of interest, not just the ones used by the receiver at the time. Then, when returning to the waypoint, other secondaries will be available if the previously used secondaries are not.

ASF correction tables were designed for first generation Loran receivers. The use of advanced propagation correction algorithms in modern receivers has eliminated the need for most mariners to refer to ASF Correction tables. Use these tables only when navigating on a chart whose TD LOP's have not been verified by actual measurement with a receiver whose ASF correction function has been disabled.

INFREQUENT LORAN OPERATIONS

1210. Use of ASF Correction Tables

The following is an example of the proper use of ASF Correction Tables.

Example: *Given an estimated ship's position of 39°N 74° 30'W, the ASF value for the Whiskey station pair of chain 9960.*

Solution: *Enter the Whiskey station pair table with the correct latitude and longitude. See Figure 1210. Extract a value of -0.9 µsec. This value would then be added to the observed time difference to compute the corrected time difference.*

INTRODUCTION TO OMEGA

1211. System Description

Omega is a worldwide, internationally operated radio navigation system. It operates in the Very Low Frequency (VLF) band between 10 and 14 kHz. It provides an all weather, medium-accuracy navigation service to marine navigators. The system consists of eight widely-spaced transmitters. Figure 1211 gives the location of these stations.

There is no master-secondary relationship between the Omega stations as there is between Loran C stations. The navigator is free to use any station pair that provides the most accurate line of position. Additionally, Omega measures phase differences between the two signals whereas Loran C measures time delays between signal receptions.

Common Frequencies:

10.2 kHz 11.05 kHz 11-1/3 kHz 13.6 kHz

Unique Frequencies:

Station	Frequency (kHz)
A: Norway	12.1
B: Liberia	12.0
C: Hawaii	11.8
D: North Dakota	13.1
E: La Reunion	12.3
F: Argentina	12.9
G: Australia	13.0
H: Japan	12.8

Figure 1211. Omega stations and frequencies.

1212. Signal Format

Each Omega station transmits on the following frequencies: 10.2 kHz, 11.05 kHz, 11.3 kHz, and 13.6 kHz. In addition to these common frequencies, each station transmits on a unique frequency given in Figure 1212. No two stations transmit the same frequency at the same time, and there is no overlap of transmissions. Each transmission segment is between 0.9 and 1.2 seconds long, with a 0.2 second interval between segments. Each station continuously repeats its transmission cycle.

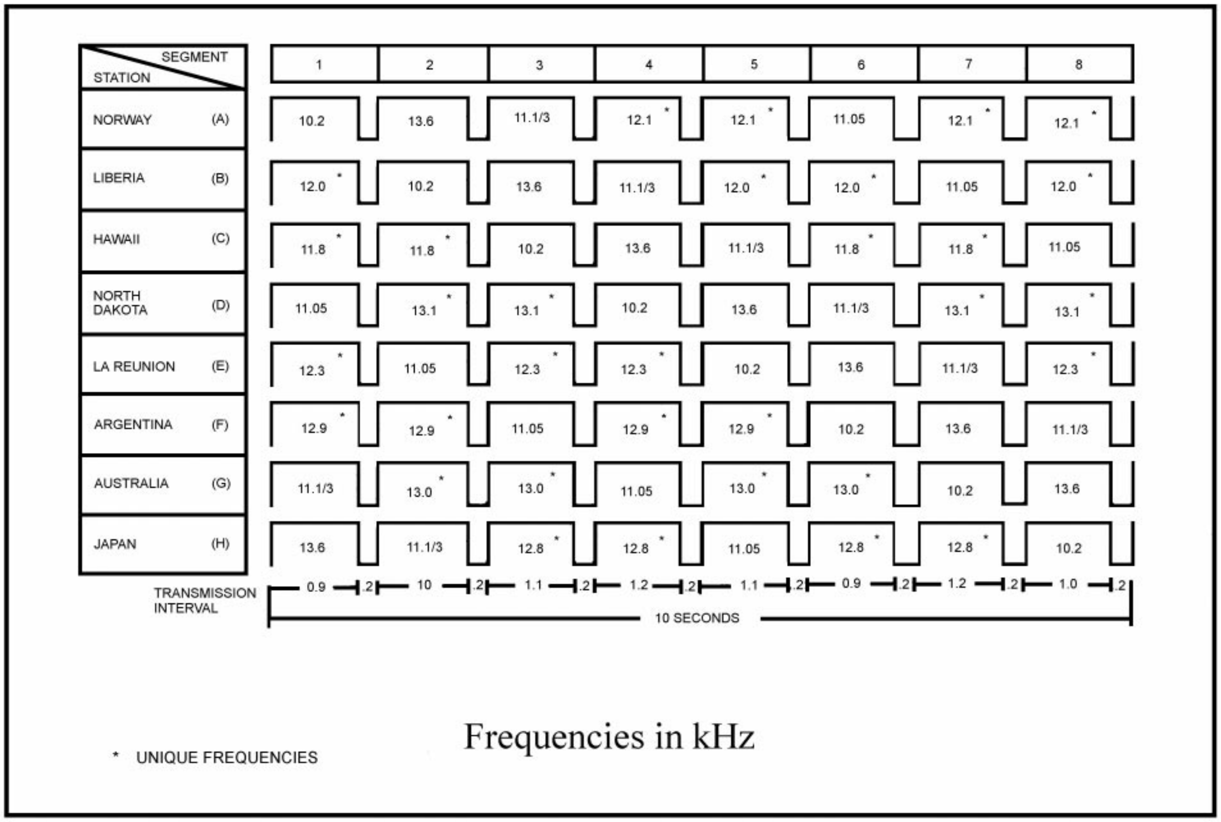


Figure 1212. Transmission format.

BASIC OMEGA OPERATION

An Omega receiver determines position in either the **direct ranging mode** or the **hyperbolic mode**. Some call the direct ranging mode the **rho-rho mode**. In the direct ranging mode, the receiver measures ranges from stations by measuring phase shifts between transmitted signals and an internal reference signal. In the hyperbolic mode, the receiver measures position relative to transmitter pairs by making phase comparisons between signals coming from these pairs.

1213. Direct Ranging Mode

The Omega wavelength, at 10.2 kHz, is approximately 16 miles long. The wavelength defines the width of each Omega "lane." See Figure 1213a. This figure shows the lanes as concentric circles formed around the transmitting station. An Omega receiver measures the phase of the received signal within a known lane. This phase shift allows the receiver to determine its position's fraction distance between lanes. Knowing which lane it is in and the fractional distance between lane boundaries, the receiver can calculate an LOP. The LOP is the line of points corresponding to the fractional distance between lanes calculated by the receiver.

The schematic of Figure 1213a does not take into account that the transmitted navigation signal forming the Omega lane is not stationary. Rather, it propagates at the speed of light. To account for this moving wave, the receiver generates a reference signal at the same frequency of the Omega navigation signal. This reference signal "freezes" the Omega signal from the receiver's perspective in a manner analogous to the way a strobe light flashing at the same frequency of a rotating disk freezes the disk from an observer's perspective. Comparing these "frozen" reference and navigation signals allows the receiver to measure the phase difference between the navigation signal and the reference signal. This phase difference, in turn, is proportional to the

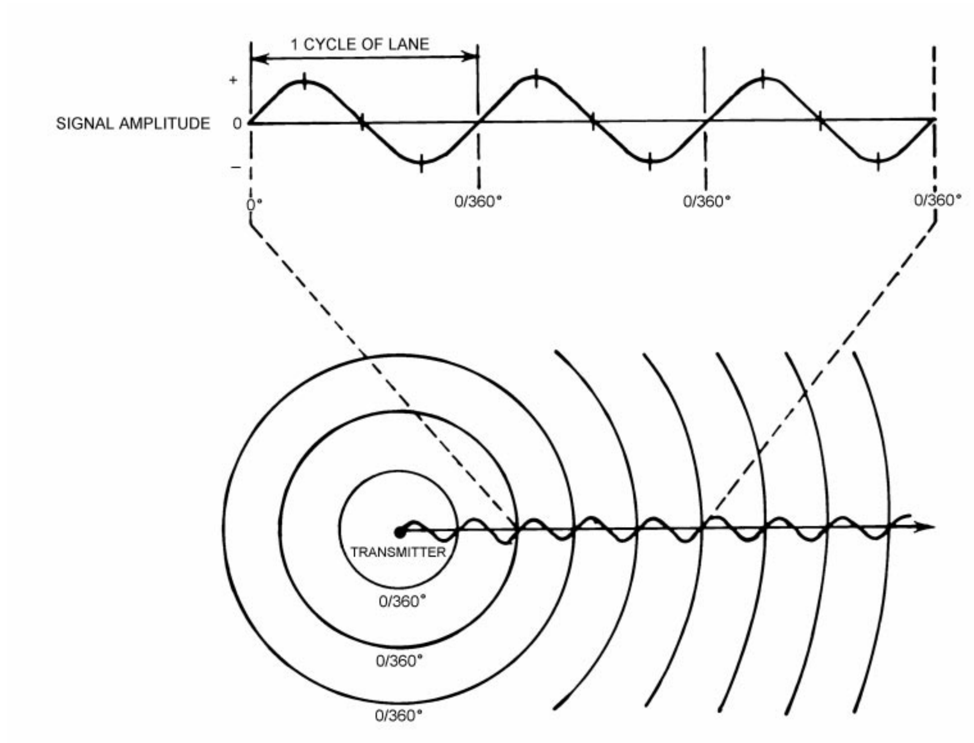


Figure 1213a. Omega lanes formed by radio waves.

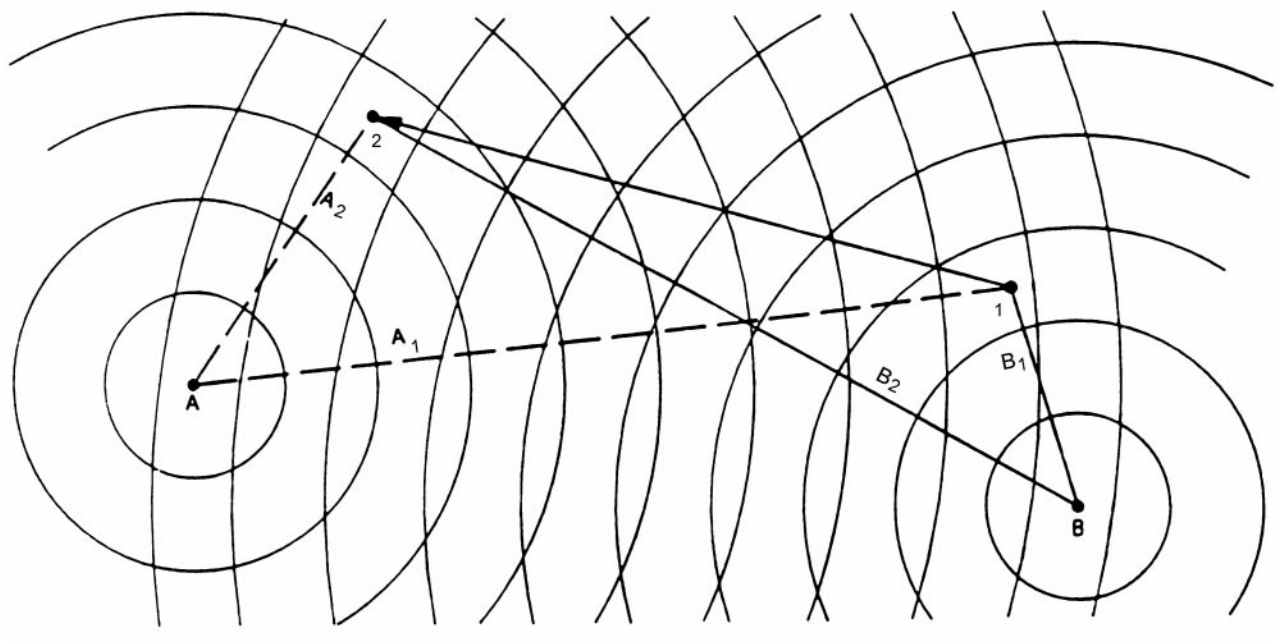


Figure 1213b. Position fixing in the direct ranging mode.

receiver's fractional distance between two Omega lanes.

See Figure 1213b for an illustration of how the direct ranging mode works. The operator initializes the Omega receiver at point 1. This initialization tells the receiver what lane it is in and the fractional distance between the lane boundaries. From this information, the receiver calculates A_1 and B_1, the distances between the receiver and stations A and B, respectively. The receiver then travels to point 2.

During the trip to point 2, the receiver keeps track of how many lanes it crosses. When it stops, it determines the fractional distance between lane boundaries at point two. From the lane counting and the phase comparison at point 2, the receiver calculates A_2 and B_2, the distances between the receiver and stations A and B, respectively.

1214. Hyperbolic Mode

In the direct range mode discussed above, the receiver measured the distance between it and two or more transmitting stations to determine lines of position. In the hyperbolic mode, the receiver measures the difference in phase between two transmitters.

See Figure 1214. This figure shows two transmitting stations, labeled A and B. Both of these stations transmit on the same frequency. Additionally, the stations transmit such that their waves' phase is zero at precisely the same time. Because each signal's phase is zero at each wave front, the phase difference where the wave fronts intersect is zero. Connecting the intersecting wave fronts yields a line along which the phase difference between the two signals is zero. This line forms a hyperbola called an **isophase contour**. At any point along this contour, the phase difference between the stations is zero. At any point between the isophase contours, there is a phase difference in the signals proportional to the fractional distance between the contours.

The set of isophase contours between station pairs forms a series of lanes, each corresponding to one complete cycle of phase difference. The hyperbolic mode lane width on the stations' baseline equals one-half the signal wavelength. For a 10.2 kHz signal, the baseline lane width is approximately 8 miles. Each of these 8 mile wide lanes is divided into 100 **centilanes (cels)**. The receiver measures the phase difference between stations in hundredths of a cycle. These units are termed **centicycles (cec)**.

1215. Direct Ranging And Hyperbolic Operation

Originally, the hyperbolic mode was more accurate because the direct ranging mode required a precise receiver

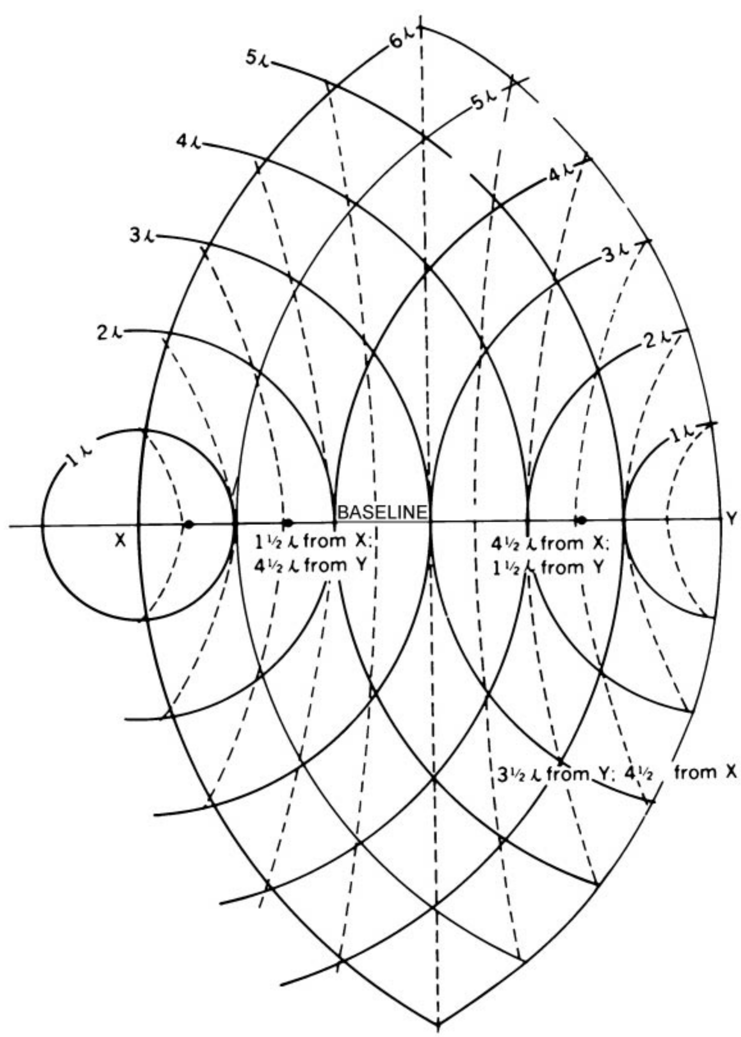


Figure 1214. Omega lanes formed by hyperbolic isophase contours.

internal oscillator to remain synchronized with the atomic oscillators used by the transmitting station. Since these oscillators would have made the receiver prohibitively expensive, the receiver carried an oscillator that was subject to clock error. In the direct ranging mode, this clock error would have been critical because this mode relies on a direct comparison between one transmitter's signal and the clock internal oscillator. In the hyperbolic mode, the receiver measures the phase difference between two transmitted signals and the receiver's internal oscillator. When the receiver subtracts one phase difference from another to calculate the difference, the clock error is mathematically eliminated. In other words, as long as the clock error remained constant between the two measurements, subtracting the two phase differences canceled out the error.

The microprocessing of modern receivers, however, allows the direct ranging mode to be used. The methodology used is similar to that used by the Global Positioning System to account for inaccuracies in GPS receiver clocks. See section 1105. The Omega receiver makes three ranging measurements and looks at the intersection of the three resulting LOP's. If there were no clock error present, the LOP's would intersect at a pinpoint. Therefore, the receiver subtracts a constant clock error from each LOP until the fix is reduced to a pinpoint. This technique allows a receiver to use the direct ranging method without a precise atomic oscillator. This technique works only if the clock error is constant for each phase difference measurement.

1216. Using Multiple Frequencies

To this point, this chapter has discussed Omega operation involving only the 10.2 kHz signal. 10.2 kHz is the primary navigation frequency because virtually all Omega receivers use this frequency. More sophisticated receivers, however, use a combination of all the available frequencies in computing a fix. Each receiver operates differently. Consult the operator's manual for a detailed discussion on how a specific receiver operates.

The above discussion on Omega operations assumed that the 10.2 kHz measurements required to calculate a fix were measured simultaneously. However, Figure 1212 shows that no two stations transmit 10.2 kHz simultaneously. Therefore, the receiver makes the 10.2 kHz phase measurements several minutes apart. In both the direct ranging and hyperbolic modes, the receiver stores the first phase difference measurement between the received signal and the receiver's internal oscillator in memory and then compares that stored value with a second phase difference measured later. The fix error caused by the slight delay between measuring station signals would be inconsequential for marine navigators because of the relative slowness of their craft. Receivers on aircraft, however, because of their craft's relatively high speed, must have a technique to advance the phase difference measured first to the time of the second phase difference measurement. This technique is called **rate aiding**.

OMEGA UNDER ICE OPERATIONS

1217. Under Ice Operation

For most military marine navigation applications, GPS has eclipsed Omega as the primary open ocean electronic navigation system. There is one area, however, in which military navigators use Omega as the primary electronic fix source: submarine operations under the polar ice cap.

Under the ice, the submarine cannot raise any antennas capable of copying GPS signals. However, VLF signals can penetrate the ice. Therefore, the submarine can deploy a **floating wire antenna (FWA)** that rises from the submerged submarine to the bottom of the ice overhead. The submarine then copies the Omega signals through the ice on the FWA.

Even though Omega is the only external electronic fix source available under the ice, its accuracy is seldom sufficient to ensure ship safety or mission accomplishment. Submarines, for example, must accurately plot the positions of thin ice regions in the event they must return to emergency surface. Omega does not position the ship with sufficient accuracy to do this. Submarines, therefore, use the inertial navigator as the primary positioning method when operating under the ice. When sufficient sounding data is available on their charts, submarine navigators supplement the inertial navigator with bottom contour navigation. Omega does, however, provide a useful backup in the under ice environment because no navigator feels comfortable navigating with only one positioning source, even if it is as accurate as the submarine inertial navigator.

VLF SIGNAL PROPAGATION

1218. Ionosphere Effects On VLF Propagation

The propagation of very-low-frequency (VLF) electromagnetic waves in the region between the lower portion of the ionosphere and the surface of the earth may be described in much the same manner as the propagation of higher frequency waves in conventional waveguides. These waves' transmission can be described by "the natural modes of propagation," or simply "modes." The behavior of the VLF wave may be discussed in terms of these modes of propagation.

There are three parameters that indicate how a certain mode will propagate in the earth-ionosphere waveguide: its attenuation rate, its excitation factor, and its phase velocity. The **attenuation rate** defines how fast energy is lost by the mode during its travel. The **excitation factor** measures how strongly the source generates the mode in comparison to other modes. **Phase velocity** defines the mode's speed and direction of travel. The modes are usually ordered by increasing attenuation rates, so that normally mode 1 has the lowest rate. For frequencies in the 10 kHz to 14 kHz band, the attenuation rates for the second and higher modes are so high that only the first mode is of any practical importance at very long distances. However, since mode 2 is more strongly excited than mode 1 by the type of transmitters used in the Omega system, both modes must be considered at intermediate distances.

Another consideration is that the modes have different phase velocities. Thus, as modes propagate outward from the transmitter, they move in and out of phase with one another, so that the strength of the vertical electric field of the signal displays "dips" or "nulls" at several points. These nulls gradually disappear, however, as mode 2 attenuates, so that the strength behaves in a smooth and regular manner at long distances (where mode 1 dominates).

Since the degree of modal interference is also dependent upon factors other than proximity to the transmitter, the minimum distance for reliable use is variable. For applications sensitive to spatial irregularities, such as lane resolution, the receiver should be at least 450 miles from the transmitter. Lesser separations may be adequate for daylight path propagation at 10.2 kHz. As a warning, the Omega LOPs depicted on charts are dashed within 450 nautical miles of a station.

Since the characteristics of the Omega signal are largely determined by the electromagnetic properties of the lower ionosphere and the surface of the earth, any change in these properties along a propagation path will generally affect the behavior of these signals. Of course, the changes will not all produce the same effect. Some will lead to small effects due to a relatively insensitive relationship between the signal characteristics and the corresponding properties. For Omega signals, one of the most important properties in this category is the effective height of the ionosphere. This height is about 90 kilometers (km) at night, but decreases quite rapidly to about 70 km soon after sunrise due to the ionization produced by solar radiation.

The phase velocity of mode 1 is inversely proportional to the ionosphere's height. Therefore, the daily changing ionosphere height causes a regular diurnal phase change in mode 1. The exact magnitude of this diurnal variation depends on several factors, including the geographic position of the receiver and transmitter and the orientation of the path relative to the boundary between the day and night hemispheres. This diurnal variation in phase is the major variation in the characteristics of the Omega signal at long distances.

Finally, the presence of a boundary between the day and night hemispheres may produce an additional variation. In the night hemisphere, both mode 1 and mode 2 are usually present. In the day hemisphere, however, only mode 1 is usually present. Hence, as the signal passes from the night to the day hemisphere, mode 2 will be converted into the daytime mode 1 at the day-night boundary. This resultant mode 1 may then interfere with the nighttime mode 1 passing unchanged into the day hemisphere. Thus, some additional variation in the characteristics may be present due to such interference.

1219. Geophysical Effects On VLF Propagation

Effects less pronounced than those associated with diurnal phase shifts are produced by various geophysical parameters including:

- Ground conductivity. Freshwater ice caps cause very high attenuation.
- Earth's magnetic field. Westerly propagation is attenuated more than easterly propagation.
- Solar activity. See the discussions of Sudden Ionospheric Disturbances and Polar Cap Absorption below.
- Latitude. The height of the ionosphere varies proportionally with latitude.

1220. Sudden Ionospheric Disturbances (SID's)

These disturbances occur when there is a very sudden and large increase in X-ray flux emitted from the sun. This occurs during either a solar flare or an "X-ray flare." An X-ray flare produces a large X-ray flux without producing a corresponding visible light emission. This effect, known as a **sudden phase anomaly (SPA)**, causes a phase advance in the VLF signal. SID effects are related to the solar zenith angle, and, consequently, occur mostly in lower latitude regions. Usually there is a phase advance over a period of 5 to 10 minutes, followed by a recovery over a period of about 30 to 60 minutes. Significant SID's could cause position errors of about 2 to 3 miles.

1221. The Polar Cap Disturbance (PCD's)

The polar cap disturbance results from the earth's magnetic field focusing particles released from the sun during a solar proton event. High-energy particles concentrate in the region of the magnetic pole, disrupting normal VLF transmission.

This effect is called the **polar cap disturbance (PCD)**. Its magnitude depends on how much of the total transmission path crosses the region near the magnetic pole. A transmission path which is entirely outside the arctic region will be unaffected by the PCD. The probability of a PCD increases during periods of high solar activity. The Omega Propagation Correction Tables make no allowances for this random phenomenon.

PCD's may persist for a week or more, but a duration

of only a few days is more common. HYDROLANT/HYDROPAC messages are originated by the Defense Mapping Agency Hydrographic/Topographic Center if significant PCD's are detected.

The position error magnitude will depend upon the positioning mode in use and the effect of the PCD on each signal. If the navigator is using the hyperbolic mode and has chosen station pairs with similar transmission paths, the effect will largely be canceled out. If using the direct ranging mode, the navigator can expect a position error of up to 8 miles.

1222. Arctic Paths And Auroral Zones

The predicted propagation corrections include allowance for propagation over regions of very poor conductivity, such as Greenland and parts of Iceland. Little data are available for these areas, hence even the best estimates are uncertain. In particular, rather rapid attenuation of the signal with position occurs as one passes into the "shadow" of the Greenland ice cap.

The auroral zones surrounding the north and south geomagnetic poles affect the phase of VLF signals. Auroral effects are believed to arise from electron precipitation in the higher regions of the ionosphere. Although the visual auroral zone is generally oval in shape, the affected region near the geomagnetic poles may be circular. Thus, auroral effects occur in a circular band between 60° and 80° north and south geomagnetic latitude. This effect slows the phase velocity of the VLF signal. This effect is approximately four times as severe at night.

INFREQUENT OMEGA OPERATIONS

As the VLF signal propagates through the atmosphere, it suffers distortion from the atmospheric phenomena discussed above. Most of these phenomena can be modeled mathematically, and receiver software can automatically correct for them. After initializing the receiver with the correct position, the receiver displays the vessel's latitude and longitude, not the measured phase differences. All modern receivers have this correction capability. Therefore, a navigator with a modern receiver will seldom need to use the Propagation Correction Tables. However, if a mariner is navigating with a first generation receiver which does not automatically make propagation corrections, then he must use these Correction Tables before plotting his LOP on the chart.

1223. Manually Correcting Omega Readings

The following is an example of the correction process.

Example: *A vessel's DR position at 1200Z on January 23 is 16°N, 40°W. The navigator, operating Omega in the hyperbolic mode, chooses stations A (Norway) and C (Hawaii) to obtain an LOP. The Omega receiver readout is 720. 12. (720 full cycles + 12 centicycles). Correct this reading for plotting on the chart.*

First, examine the Omega Table Area chart to determine the area corresponding to the vessel's DR position. A DR position of 16°N 40°W corresponds to area 12. Figure 1223a shows this chart.

Next, obtain the proper Omega Propagation Correction Tables. There will be two separate volumes in this example. There will be an area 12 volume for the Norwegian station and an area 12 volume for the Hawaiian station. Inside each volume is a Page Index to Propagation Corrections. This index consists of a chartlet of area 12 subdivided into smaller areas. Figure 1223b shows the index for the Norwegian station in area 12. Again using the ship's DR position, find the section of the index corresponding to 16°N 40°W. Inspecting Figure 1223b shows that the DR position falls in section 39. That indicates that the proper correction is found on page 39 of the Correction Table. Go to page 39 of the table.

The entering arguments for the table on page 39 are date and GMT. The date is January 23 and GMT is 1200. The correction corresponding to these arguments is -0.06 cec. See Figure 1223c.

Following the same process in the Area 12 Correction volume for the Hawaiian station yields a correction of –0.67 cec.

To obtain a station pair correction, subtract the correction for the station with the higher alphabetical designator from the correction for the station with the lower designator. In this example, Hawaii's station designator (C) is higher than Norway's station designator (A). Therefore, the station pair correction is (–0.06 cec) – (–0.67 cec) = +0.61 cec.

1224. Lane Identification

The receiver's lane counter, set on departure from a known position, will indicate the present lane unless it looses its lane counting capability. In that case, the navigator can determine his lane by either dead reckoning or using the procedure described below.

Using a receiver capable of tracking multiple frequencies, compute a 3.4 kHz lane by subtracting the corrected 10.2 kHz phase reading from a corrected 13.6 kHz phase reading. Since the 3.4 kHz lane is 24 miles wide, the navigator need know his position only within 12 miles to identify the correct 3.4 kHz "coarse" lane. This "coarse" lane is formed by three 10.2 kHz "fine" lanes; all 3.4 kHz coarse lanes are bounded by 10.2 kHz lanes evenly divisible by three. Determine and plot the computed 3.4 kHz phase difference in relation to the derived 3.4 kHz coarse lane to determine the correct 10.2 kHz fine lane in which the vessel is located. Having determined the correct 10.2 kHz lane, the

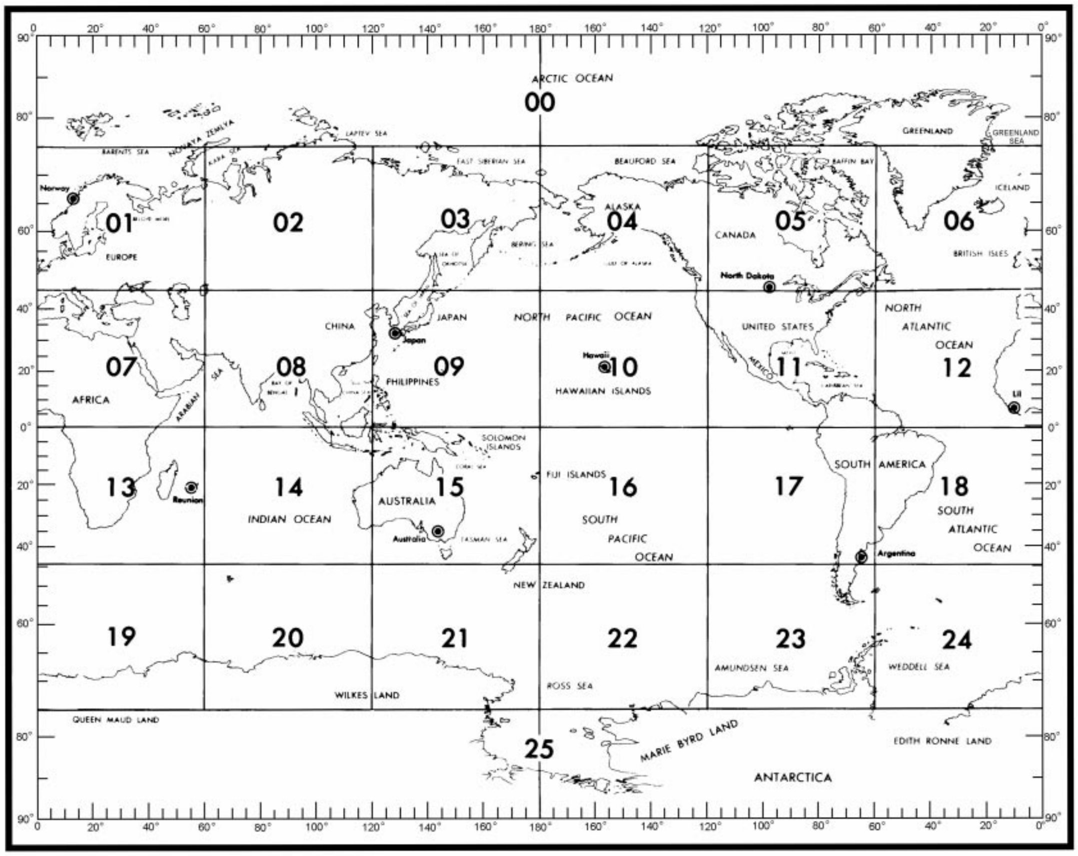


Figure 1223a. Omega table areas.

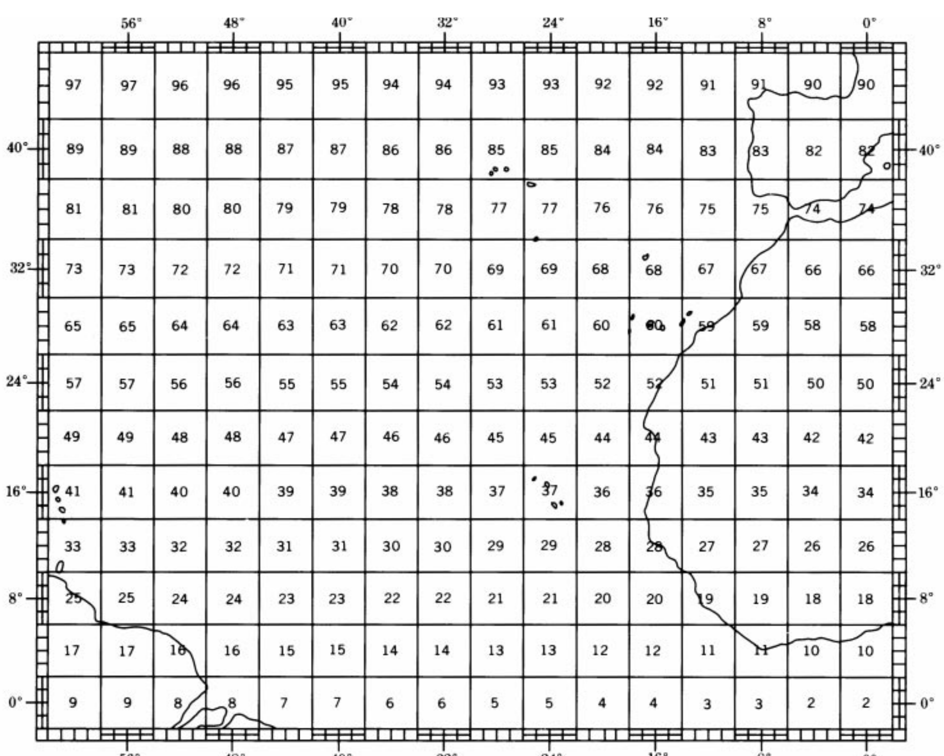


Figure 1223b. Page index to propagation correction.

10.2 KHZ OMEGA PROPAGATION CORRECTIONS IN UNITS OF CECS — LOCATION 16.0 N 40.0 W — STATION A NORWAY

DATE	GMT 00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
1-15JAN	-68	-68	-68	-68	-68	-68	-68	-68	-65	2	8	-9	-8	-6	-6	-8	-12	-19	-28	-41	-55	-63	-66	-67	-68	
16-31JAN	-68	-68	-68	-68	-68	-68	-68	-68	-60	6	6	-10	-6	-3	-3	-5	-9	-16	-25	-37	-52	-62	-65	-67	-68	
1-14FEB	-68	-68	-68	-68	-68	-68	-68	-66	-47	12	2	-7	-1	1	1	-1	-5	-11	-21	-33	-49	-61	-65	-67	-68	
15-29FEB	-68	-68	-68	-68	-68	-68	-67	-57	-32	12	-1	-2	2	4	4	2	-2	-7	-16	-28	-45	-59	-64	-67	-68	
1-15MAR	-67	-67	-68	-68	-68	-68	-61	-46	-19	9	-1	2	4	6	6	6	2	-3	-11	-23	-41	-57	-63	-66	-67	
16-31MAR	-67	-67	-68	-68	-68	-63	-54	-37	-9	8	0	3	6	7	8	7	5	1	-7	-18	-36	-55	-62	-66	-67	
1-15APR	-67	-67	-68	-68	-63	-54	-44	-27	0	5	2	5	7	9	9	9	7	4	-2	-12	-30	-52	-60	-65	-67	
16-30APR	-66	-67	-67	-65	-56	-49	-38	-21	6	4	3	6	8	10	10	10	8	6	1	-7	-25	-48	-58	-64	-66	
1-15MAY	-65	-66	-65	-61	-53	-44	-32	-15	7	4	4	7	9	11	11	10	9	7	3	-3	-18	-42	-54	-62	-65	
16-31MAY	-64	-65	-65	-62	-51	-43	-29	-13	7	4	5	8	10	11	12	11	10	7	4	0	-13	-36	-51	-59	-64	
1-15JUN	-62	-63	-64	-61	-51	-41	-28	-11	7	4	5	8	10	12	12	11	10	8	5	1	-8	-30	-49	-57	-62	
16-30JUN	-61	-63	-63	-61	-50	-41	-28	-11	7	4	5	8	10	12	12	11	10	8	5	2	-6	-27	-48	-56	-61	
1-15JUL	-61	-63	-64	-61	-55	-41	-30	-13	7	5	5	8	10	11	12	11	10	8	5	2	-6	-28	-48	-56	-61	
16-31JUL	-63	-65	-65	-62	-54	-44	-31	-15	6	5	4	7	10	11	12	11	10	8	5	1	-9	-32	-50	-58	-63	
1-15AUG	-65	-66	-65	-59	-52	-47	-35	-17	5	5	4	7	9	11	11	11	9	7	4	-2	-15	-39	-53	-61	-65	
16-31AUG	-66	-67	-67	-65	-56	-49	-38	-23	4	5	3	6	8	10	10	10	8	6	2	-6	-22	-46	-57	-63	-66	
1-15SEP	-67	-67	-68	-67	-64	-55	-44	-26	5	5	2	5	7	9	9	9	7	3	-3	-14	-33	-53	-61	-65	-67	
16-30SEP	-67	-67	-68	-68	-67	-61	-47	-32	2	5	1	4	6	8	8	7	5	-1	-9	-20	-40	-57	-63	-66	-67	
1-15OCT	-67	-67	-68	-68	-68	-66	-56	-38	0	5	-2	3	5	6	6	4	0	-7	-16	-29	-48	-60	-64	-66	-67	
16-31OCT	-67	-67	-68	-68	-68	-68	-64	-49	-7	7	-5	1	3	4	3	0	-4	-12	-21	-36	-53	-61	-65	-67	-67	
1-15NOV	-67	-67	-67	-68	-68	-68	-68	-60	-23	12	-6	-4	-1	0	0	-3	-9	-17	-27	-41	-56	-62	-65	-67	-67	
16-30NOV	-67	-67	-67	-68	-68	-68	-68	-66	-42	13	-2	-8	-4	-3	-3	-6	-11	-20	-29	-43	-57	-63	-66	-67	-67	
1-15DEC	-67	-67	-67	-68	-68	-68	-68	-68	-60	13	5	-10	-7	-6	-6	-9	-14	-21	-31	-44	-57	-63	-66	-67	-67	
16-31DEC	-67	-67	-67	-68	-68	-68	-68	-68	-64	8	7	-10	-9	-7	-7	-9	-14	-21	-30	-43	-56	-63	-66	-67	-67	

Figure 1223c. Omega Propogation Correction Tables for 10.2 kHz, Station A, at 16˚N, 40˚ W.

navigator can reset his receiver to the proper lane count.

Example: *A vessel's 200700Z Jan DR position is 51° 26'N, 167°32'W. The receiver has lost the lane count but the 0700Z phase readings for pair A-C are 0.19 centicycles for 10.2 kHz and 0.99 centicycles for 13.6 kHz. Determine the correct 10.2 kHz fine lane. See Figure 1224.*

To solve the problem, first plot the vessel's DR position. Use Omega plotting sheet 7609. Then determine the 10.2 kHz lanes evenly divisible by three between which the DR position plots. Inspecting the DR position on chart 7609 shows that the position falls between lanes A-C 1017 and A-C 1020. These lanes mark the boundary of the 3.4 kHz coarse lane. Then, determine the propagation correction for both the 10.2 kHz and 13.6 kHz signals from the Propagation Correction Tables for both frequencies, and apply these corrections to the measured phase difference to obtain the corrected phase difference.

Inspecting the tables yields the following results:

Correction for Station A (13.6 kHz) = – 1.42 cec
Correction for Station C (13.6 kHz) = – 0.89 cec
Correction for Station A (10.2 kHz) = – 0.54 cec
Correction for Station C (10.2 kHz) = – 0.45 cec
Corrected 13.6 kHz reading = 0.99 cec + (– 1.42 cec) – (– 0.89 cec) = 0.46 cec.
Corrected 10.2 kHz reading = 0.19 cec + (– 0.54 cec) – (– 0.45 cec) = 0.10 cec
Corrected 3.4 kHz derived reading = 0.46 cec – 0.10 cec = 0.36 cec.

Therefore, the vessel's position lies 36% of the way from lane A-C 1017 to lane A-C 1020. Use this information to determine that the correct 10.2 kHz fine lane is lane A-C 1018. Combining the proper lane with the 10.2 kHz corrected reading yields the correct Omega LOP: A-C 1018.10.

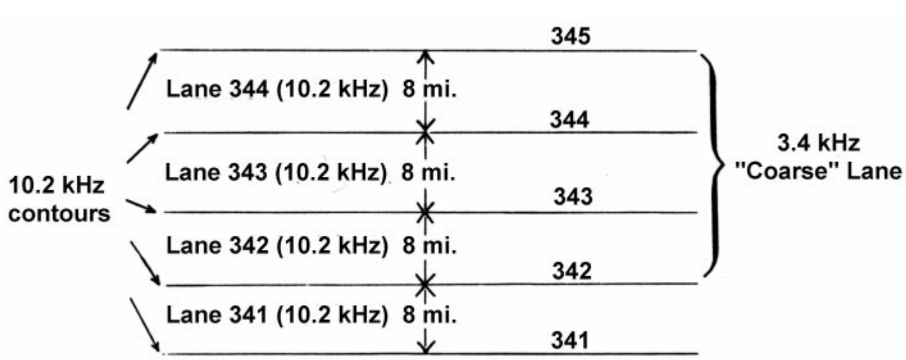


Figure 1224. The coarse lane.

CHAPTER 13

RADAR NAVIGATION

PRINCIPLES OF RADAR OPERATION

1300. Introduction

Radar determines distance to an object by measuring the time required for a radio signal to travel from a transmitter to an object and return. Since most radars use directional antennae, they can also determine an object's bearing. However, a radar's bearing measurement will be less accurate than its distance measurement. Understanding this concept is crucial to ensuring the optimal employment of the radar for safe navigation.

1301. Signal Characteristics

In most marine navigation applications, the radar signal is pulse modulated. Signals are generated by a timing circuit so that energy leaves the antenna in very short pulses. When transmitting, the antenna is connected to the transmitter but not the receiver. As soon as the pulse leaves, an electronic switch disconnects the antenna from the transmitter and connects it to the receiver. Another pulse is not transmitted until after the preceding one has had time to travel to the most distant target within range and return. Since the interval between pulses is long compared with the length of a pulse, strong signals can be provided with low average power. The duration or length of a single pulse is called **pulse length**, **pulse duration**, or **pulse width**. This pulse emission sequence repeats a great many times, perhaps 1,000 per second. This rate defines the **pulse repetition rate (PRR)**. The returned pulses are displayed on an indicator screen.

1302. The Display

The most common type of radar display used in the Navy is the **plan position indicator (PPI)**. On a PPI, the sweep starts at the center of the display and moves outward along a radial line rotating in synchronization with the antenna. A detection is indicated by a brightening of the display screen at the bearing and range of the return. Because of a luminescent tube face coating, the glow continues after the trace rotates past the target. Figure 1302 shows this presentation.

On a PPI, a target's actual range is proportional to its echo's distance from the scope's center. A moveable cursor helps to measure ranges and bearings. In the "heading-upward" presentation, which indicates relative bearings, the top of the scope represents the direction of the ship's head. In this unstabilized presentation, the orientation changes as the ship changes heading. In the stabilized "north-upward" presentation, gyro north is always at the top of the scope.

1303. The Radar Beam

The pulses of energy comprising the radar beam would form a single lobe-shaped pattern of radiation if emitted in free space. Figure 1303a. shows this free space radiation pattern, including the undesirable minor lobes or side lobes associated with practical antenna design.

Although the radiated energy is concentrated into a relatively narrow main beam by the antenna, there is no clearly defined envelope of the energy radiated. The energy is concentrated along the axis of the beam. With the rapid decrease in the amount of radiated energy in directions away from this axis, practical power limits may be used to define the dimensions of the radar beam.

A radar beam's horizontal and vertical beam widths are referenced to arbitrarily selected power limits. The most common convention defines beam width as the angular width between half power points. The half power point corresponds to a drop in 3 decibels from the maximum beam strength.

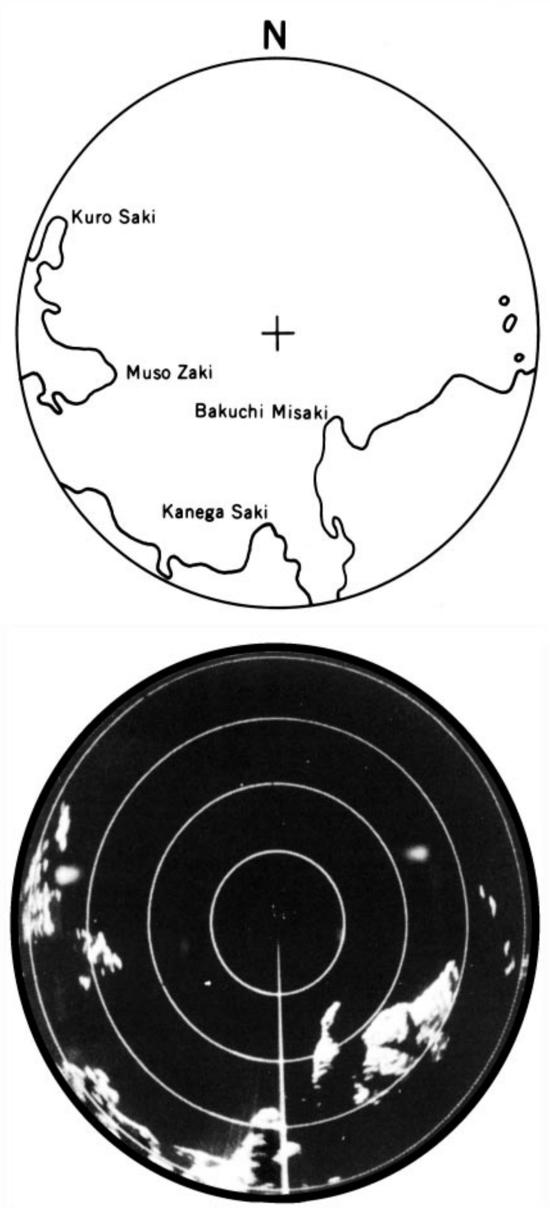
The definition of the decibel shows this halving of power at a decrease in 3 dB from maximum power. A decibel is simply the logarithm of the ratio of a final power level to a reference power level:

$$dB = 10 \log\left[\frac{P_1}{P_0}\right]$$

where P_1 is the final power level, and P_0 is a reference power level. When calculating the dB drop for a 50% reduction in power level, the equation becomes:

$$dB = 10 \log(.5)$$
$$dB = -3\ dB$$

The radiation diagram shown in Figure 1303b depicts relative values of power in the same plane existing at the same distances from the antenna or the origin of the radar beam. Maximum power is in the direction of the axis of the beam. Power values diminish rapidly in directions away from the axis. The beam width is taken as the angle



HONSHU, NW COAST-APPROACH TO MAIZURU KO
Radar position: 35°34'.1 N., 135°19'.6 E.
Range ring interval: 1 mile
(Source: Japanese Sailing Directions)

Figure 1302. Plan Position Indicator (PPI) display.

between the half-power points.

The beam width depends upon the frequency or wavelength of the transmitted energy, antenna design, and the dimensions of the antenna.

For a given antenna size (antenna aperture), narrower beam widths result from using shorter wavelengths. For a given wavelength, narrower beam widths result from using larger antennas.

With radar waves being propagated in the vicinity of the surface of the sea, the main lobe of the radar beam is composed of a number of separate lobes, as opposed to the single lobe-shaped pattern of radiation as emitted in free space. This phenomenon is the result of interference between radar waves directly transmitted, and those waves which are reflected from the surface of the sea. Radar waves strike the surface of the sea, and the indirect waves reflect off the surface of the sea. See Figure 1303c. These reflected waves either constructively or destructively interfere with the direct waves depending upon the waves' phase relationship.

1304. Diffraction And Attenuation

Diffraction is the bending of a wave as it passes an obstruction. Because of diffraction there is some illumination of the region behind an obstruction or target by the radar beam. Diffraction effects are greater at the lower frequencies. Thus, the radar beam of a lower frequency radar tends to illuminate more of the shadow region behind an obstruction than the beam of a radar of higher frequency or shorter wavelength.

Attenuation is the scattering and absorption of the energy in the radar beam as it passes through the atmosphere. It causes a decrease in echo strength. Attenuation is greater at the higher frequencies or shorter wavelengths.

While reflected echoes are much weaker than the transmitted pulses, the characteristics of their return to the source are similar to the characteristics of propagation. The strengths of these echoes are dependent upon the amount of transmitted energy striking the targets and the size and reflecting properties of the targets.

1305. Refraction

If the radar waves traveled in straight lines, the distance to the radar horizon would be dependent only on the power output of the transmitter and the height of the antenna. In other words, the distance to the radar horizon would be the same as that of the geometrical horizon for the antenna height. However, atmospheric density gradients bend radar rays as they travel to and from a target. This bending is called **refraction**.

The following formula, where h is the height of the antenna in feet, gives the distance to the radar horizon in nautical miles:

$$d = 1.22\sqrt{h} \ .$$

The distance to the radar horizon does not limit the distance from which echoes may be received from targets. As-

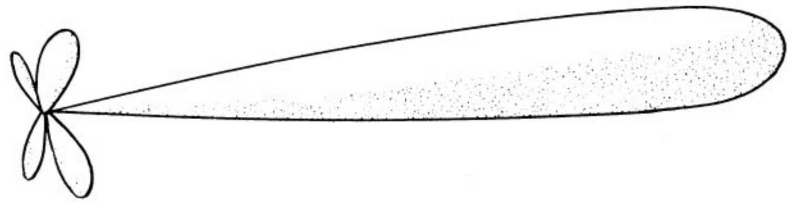


Figure1303a. Freespace radiation pattern.

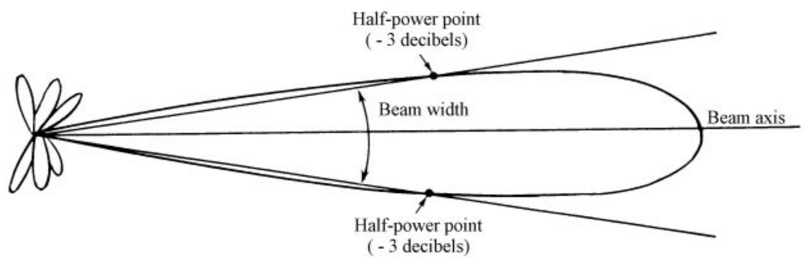


Figure1303b. Radiation diagram.

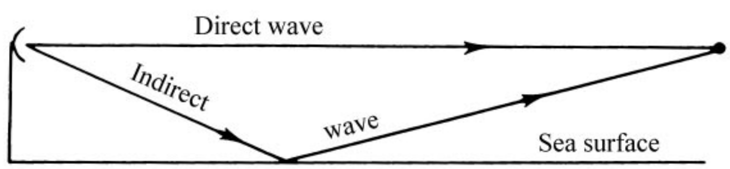


Figure1303c. Direct and indirect waves.

suming that adequate power is transmitted, echoes may be received from targets beyond the radar horizon if their reflecting surfaces extend above it. Note that the distance to the radar horizon is the distance at which the radar rays pass tangent to the surface of the earth.

1306. Factors Affecting Radar Interpretation

Radar's value as a navigational aid depends on the navigator's understanding its characteristics and limitations. Whether measuring the range to a single reflective object or trying to discern a shoreline lost amid severe clutter, knowledge of the characteristics of the individual radar used are crucial. Some of the factors to be considered in interpretation are discussed below:

- **Resolution in Range.** In part A of Figure 1306a, a transmitted pulse has arrived at the second of two targets of insufficient size or density to absorb or reflect all of the energy of the pulse. While the pulse has traveled from the first to the second target, the echo from the first has traveled an equal distance in the opposite direction. At B, the transmitted pulse has continued on beyond the second target, and the two echoes are returning toward the transmitter. The distance between leading edges of the two echoes is twice the distance between targets. The correct distance will be shown on the scope, which is calibrated to show half the distance traveled out and back. At C the targets are closer together and the pulse length has been increased. The two echoes merge, and on the scope they will appear as a single, large target. At D the pulse length has been decreased, and the two echoes appear separated. The ability of a radar to separate targets close together on the same bearing is called **resolution in range**. It is related primarily to pulse length. The minimum distance between targets that can be distinguished as separate is half the pulse length. This (half the pulse length) is the apparent depth or thickness of a target presenting a flat perpendicular surface to the radar beam. Thus, several ships close together may appear as an island. Echoes from a number of small boats, piles, breakers, or even

large ships close to the shore may blend with echoes from the shore, resulting in an incorrect indication of the position and shape of the shoreline.

- **Resolution in Bearing**. Echoes from two or more targets close together at the same range may merge to form a single, wider echo. The ability to separate targets is called **resolution in bearing**. Bearing resolution is a function of two variables: beam width and range between targets. A narrower beam and a shorter distance between objects both increase bearing resolution.

- **Height of Antenna and Target**. If the radar horizon is between the transmitting vessel and the target, the lower part of the target will not be visible. A large vessel may appear as a small craft, or a shoreline may appear at some distance inland.

- **Reflecting Quality and Aspect of Target**. Echoes from several targets of the same size may be quite different in appearance. A metal surface reflects radio waves more strongly than a wooden surface. A surface perpendicular to the beam returns a stronger echo than a non perpendicular one. For this reason, a gently sloping beach may not be visible. A vessel encountered broadside returns a stronger echo than one heading directly toward or away.

- **Frequency**. As frequency increases, reflections occur from smaller targets.

Atmospheric noise, sea return, and precipitation complicate radar interpretation by producing **clutter**. Clutter is usually strongest near the vessel. Strong echoes can sometimes be detected by reducing receiver gain to eliminate weaker signals. By watching the repeater during several rotations of the antenna, the operator can discriminate between clutter and a target even when the signal strengths from clutter and the target are equal. At each rotation, the

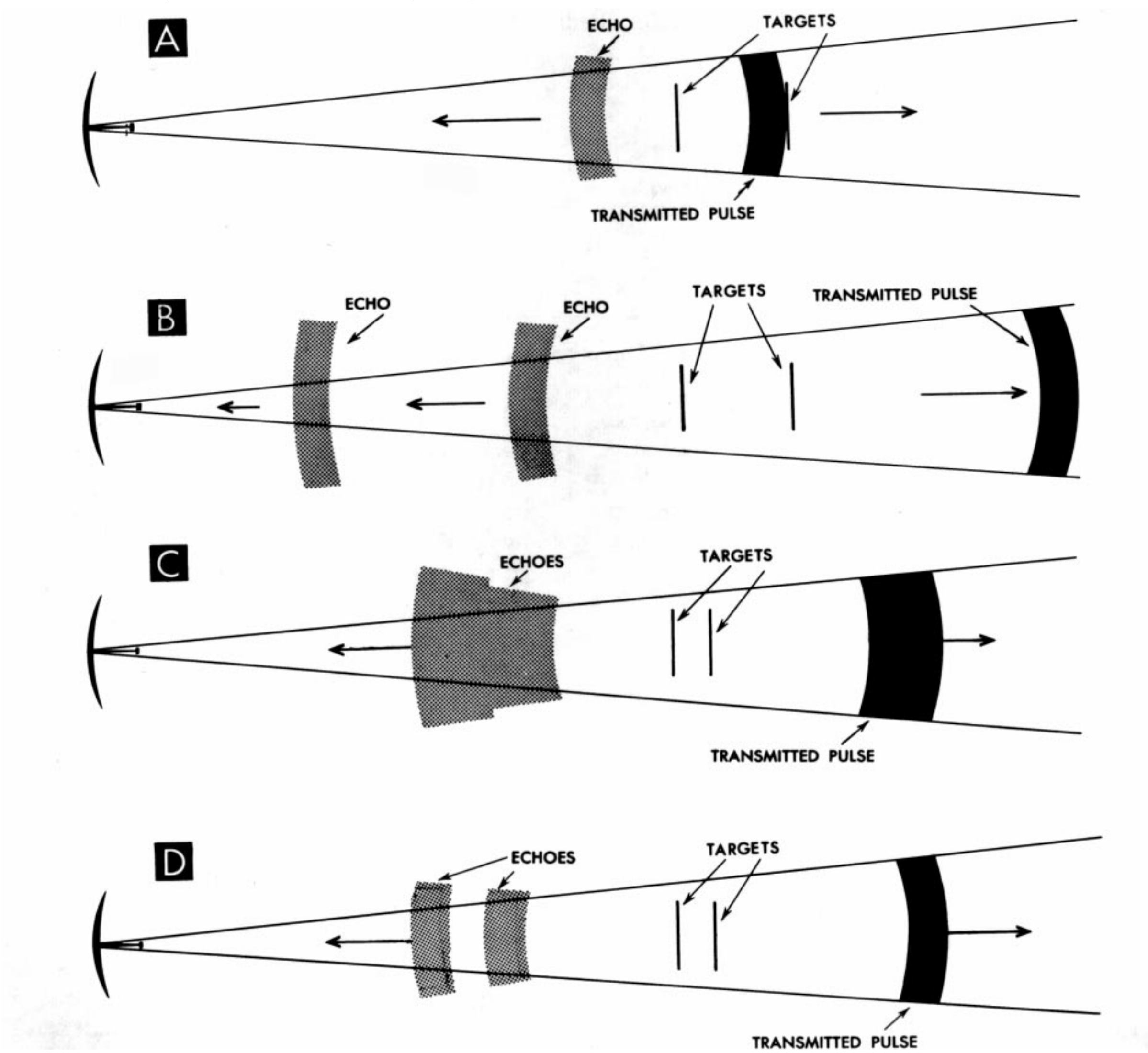


Figure 1306a. Resolution in range.

signals from targets will remain relatively stationary on the display while those caused by clutter will appear at different locations.

Another major problem lies in determining which features in the vicinity of the shoreline are actually represented by echoes shown on the repeater. Particularly in cases where a low lying shore is being scanned, there may be considerable uncertainty.

A related problem is that certain features on the shore will not return echoes because they are blocked from the radar beam by other physical features or obstructions. This factor in turn causes the chart like image painted on the scope to differ from the chart of the area.

If the navigator is to be able to interpret the presentation on his radarscope, he must understand the characteristics of radar propagation, the capabilities of his radar set, the reflecting properties of different types of radar targets, and the ability to analyze his chart to determine which charted features are most likely to reflect the transmitted pulses or to be blocked. Experience gained during clear weather comparison between radar and visual images is invaluable.

Land masses are generally recognizable because of the steady brilliance of the relatively large areas painted on the PPI. Also, land should be at positions expected from the ship's navigational position. Although land masses are readily recognizable, the primary problem is the identification of specific land features. Identification of specific features can be quite difficult because of various factors, including distortion resulting from beam width and pulse length, and uncertainty as to just which charted features are reflecting the echoes.

Sand spits and smooth, clear beaches normally do not appear on the PPI at ranges beyond 1 or 2 miles because these targets have almost no area that can reflect energy back to the radar. Ranges determined from these targets are not reliable. If waves are breaking over a sandbar, echoes may be returned from the surf. Waves may, however, break well out from the actual shoreline, so that ranging on the surf may be misleading.

Mud flats and marshes normally reflect radar pulses only a little better than a sand spit. The weak echoes received at low tide disappear at high tide. Mangroves and other thick growth may produce a strong echo. Areas that are indicated as swamps on a chart, therefore, may return either strong or weak echoes, depending on the density and size of the vegetation growing in the area.

When sand dunes are covered with vegetation and are well back from a low, smooth beach, the apparent shoreline determined by radar appears as the line of the dunes rather than the true shoreline. Under some conditions, sand dunes may return strong echo signals because the combination of the vertical surface of the vegetation and the horizontal beach may form a sort of corner reflector.

Lagoons and inland lakes usually appear as blank areas on a PPI because the smooth water surface returns no energy to the radar antenna. In some instances, the sandbar or reef surrounding the lagoon may not appear on the PPI because it lies too low in the water.

Coral atolls and long chains of islands may produce long lines of echoes when the radar beam is directed perpendicular to the line of the islands. This indication is especially true when the islands are closely spaced. The reason is that the spreading resulting from the width of the radar beam causes the echoes to blend into continuous lines. When the chain of islands is viewed lengthwise, or obliquely, however, each island may produce a separate return. Surf breaking on a reef around an atoll produces a ragged, variable line of echoes.

One or two rocks projecting above the surface of the water, or waves breaking over a reef, may appear on the PPI. When an object is submerged entirely and the sea is smooth over it, no indication is seen on the PPI.

If the land rises in a gradual, regular manner from the shoreline, no part of the terrain produces an echo that is stronger than the echo from any other part. As a result, a general haze of echoes appears on the PPI, and it is difficult to ascertain the range to any particular part of the land.

Blotchy signals are returned from hilly ground, because the crest of each hill returns a good echo although the valley beyond is in a shadow. If high receiver gain is used, the pattern may become solid except for the very deep shadows.

Low islands ordinarily produce small echoes. When thick palm trees or other foliage grow on the island, strong echoes often are produced because the horizontal surface of the water around the island forms a sort of corner reflector with the vertical surfaces of the trees. As a result, wooded islands give good echoes and can be detected at a much greater range than barren islands.

Sizable land masses may be missing from the radar display because of certain features being blocked from the radar beam by other features. A shoreline which is continuous on the PPI display when the ship is at one position, may not be continuous when the ship is at another position and scanning the same shoreline. The radar beam may be blocked from a segment of this shoreline by an obstruction such as a promontory. An indentation in the shoreline, such as a cove or bay, appearing on the PPI when the ship is at one position, may not appear when the ship is at another position nearby. Thus, radar shadow alone can cause considerable differences between the PPI display and the chart presentation. This effect in conjunction with beam width and pulse length distortion of the PPI display can cause even greater differences.

The returns of objects close to shore may merge with the shoreline image on the PPI, because of distortion effects of horizontal beam width and pulse length. Target images on the PPI always are distorted angularly by an amount equal to the effective horizontal beam width. Also, the target images always are distorted radially by an amount at least equal to one-half the pulse length (164 yards per microsecond of pulse length).

Figure 1306b illustrates the effects of ship's position, beam width, and pulse length on the radar shoreline. Because of beam width distortion, a straight, or nearly

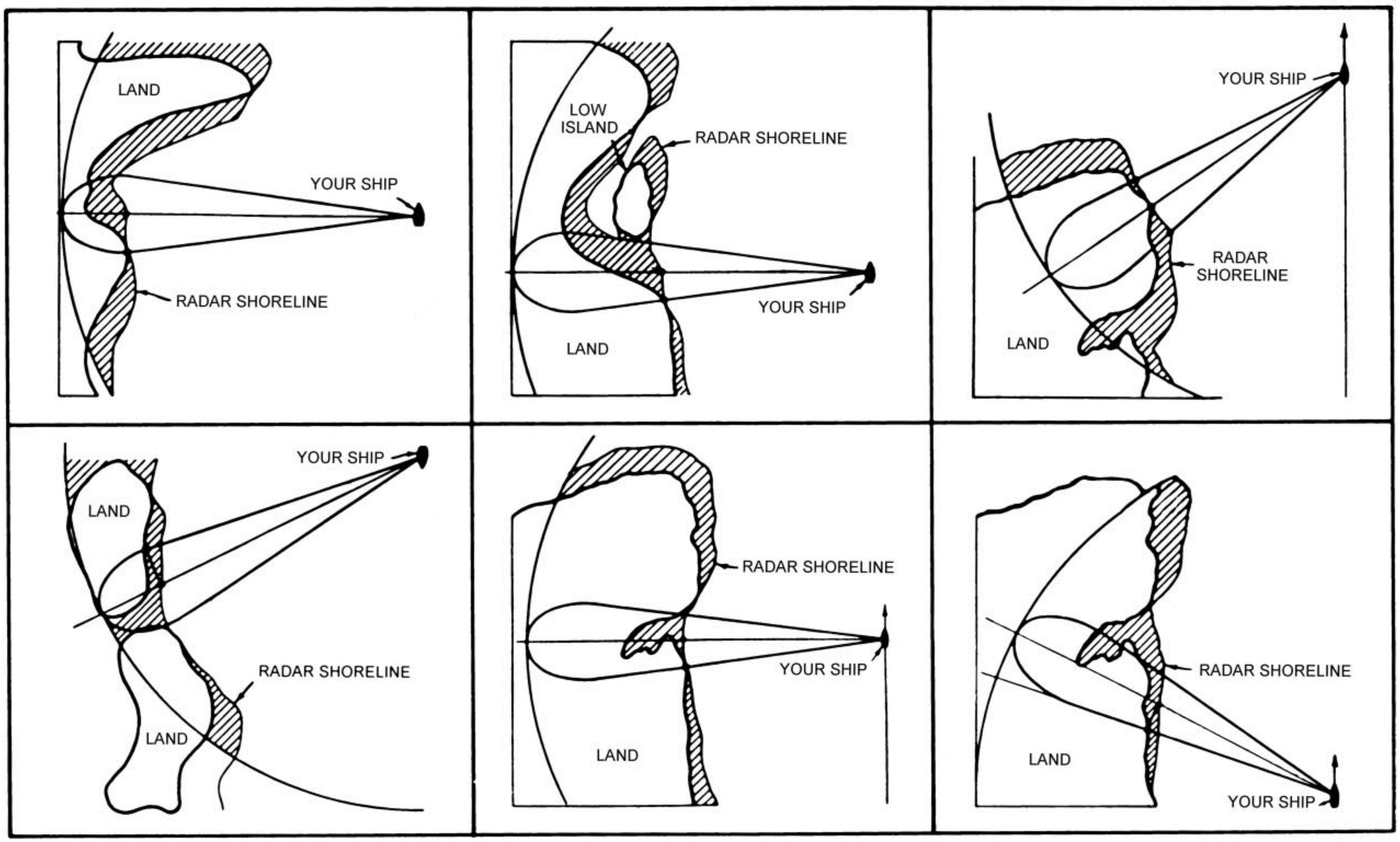


Figure 1306b. Effects of ship's position, beam width, and pulse length on radar shoreline.

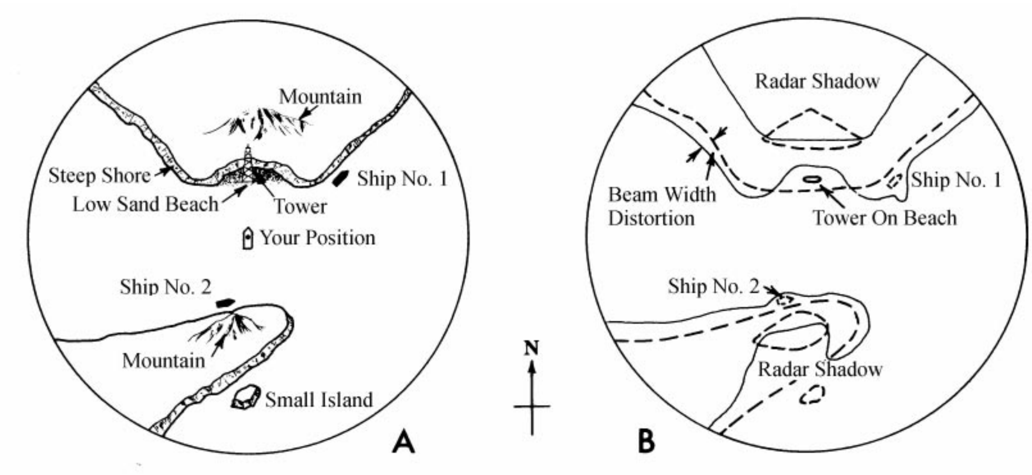


Figure 1306c. Distortion effects of radar shadow, beam width, and pulse length.

straight, shoreline often appears crescent-shaped on the PPI. This effect is greater with the wider beam widths. Note that this distortion increases as the angle between the beam axis and the shoreline decreases.

Figure 1306c illustrates the distortion effects of radar shadow, beam width, and pulse length. View A shows the actual shape of the shoreline and the land behind it. Note the steel tower on the low sand beach and the two ships at anchor close to shore. The heavy line in view B represents the shoreline on the PPI. The dotted lines represent the actual position and shape of all targets. Note in particular:

1. The low sand beach is not detected by the radar.
2. The tower on the low beach is detected, but it looks like a ship in a cove. At closer range the land would be detected and the cove-shaped area would begin to fill in; then the tower could not be seen without reducing the receiver gain.
3. The radar shadow behind both mountains. Distortion owing to radar shadows is responsible for more confusion than any other cause. The small island does not appear because it is in the radar shadow.
4. The spreading of the land in bearing caused by beam width distortion. Look at the upper shore of the peninsula. The shoreline distortion is greater to the west because the angle between the radar beam and the shore is smaller as the beam seeks out the more westerly shore.
5. Ship No. 1 appears as a small peninsula. Her return has merged with the land because of the beam width distortion.
6. Ship No. 2 also merges with the shoreline and forms a bump. This bump is caused by pulse length and beam width distortion. Reducing receiver gain might cause the ship to separate from land, provided the ship is not too close to the shore. The Fast Time Constant (FTC) control could also be used to attempt to separate the ship from land.

1307. Recognition Of Unwanted Echoes

The navigator must be able to recognize various abnormal echoes and effects on the radarscope so as not to be confused by their presence.

Indirect or false echoes are caused by reflection of the main lobe of the radar beam off ship's structures such as stacks and kingposts. When such reflection does occur, the echo will return from a legitimate radar contact to the antenna by the same indirect path. Consequently, the echo will appear on the PPI at the bearing of the reflecting surface. As shown in Figure 1307a, the indirect echo will appear on the PPI at the same range as the direct echo received, assuming that the additional distance by the indirect path is negligible.

Characteristics by which indirect echoes may be recognized are summarized as follows:

1. The indirect echoes will usually occur in shadow sectors.
2. They are received on substantially constant bearings, although the true bearing of the radar contact may change appreciably.
3. They appear at the same ranges as the corresponding direct echoes.
4. When plotted, their movements are usually abnormal.
5. Their shapes may indicate that they are not direct echoes.

Side-lobe effects are readily recognized in that they produce a series of echoes (Figure 1307b) on each side of the main lobe echo at the same range as the latter. Semicircles, or even complete circles, may be produced. Because of the low energy of the side-lobes, these effects will normally

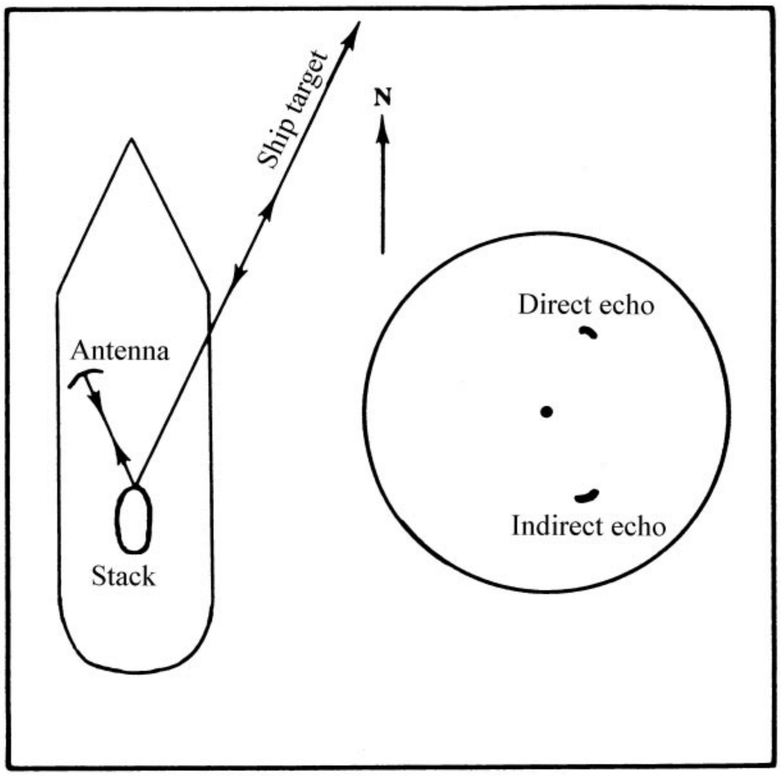


Figure 1307a. Indirect echo.

occur only at the shorter ranges. The effects may be minimized or eliminated, through use of the gain and anti-clutter controls. Slotted wave guide antennas have largely eliminated the side-lobe problem.

Multiple echoes may occur when a strong echo is received from another ship at close range. A second or third or more echoes may be observed on the radarscope at double, triple, or other multiples of the actual range of the radar contact (Figure 1307c).

Second-trace echoes (multiple-trace echoes) are echoes received from a contact at an actual range greater than the radar range setting. If an echo from a distant target is received after the following pulse has been transmitted, the echo will appear on the radarscope at the correct bearing but not at the true range. Second-trace echoes are unusual, except under abnormal atmospheric conditions, or conditions under which super-refraction is present. Second-trace echoes may be recognized through changes in their positions on the radarscope in changing the pulse repetition rate (PRR); their hazy, streaky, or distorted shape; and the erratic movements on plotting.

As illustrated in Figure 1307d, a target return is detected on a true bearing of 090° at a distance of 7.5 miles. On changing the PRR from 2,000 to 1,800 pulses per second, the same target is detected on a bearing of 090° at a distance of 3 miles (Figure 1307e). The change in the position of the return indicates that the return is a second-trace echo. The actual distance of the target is the distance as indicated on the PPI plus half the distance the radar wave travels between pulses.

Electronic interference effects, such as may occur when near another radar operating in the same frequency band as that of the observer's ship, is usually seen on the PPI as a large number of bright dots either scattered at random or in the form of dotted lines extending from the center to the edge of the PPI.

Interference effects are greater at the longer radar range scale settings. The interference effects can be distinguished easily from normal echoes because they do not appear in the same places on successive rotations of the antenna.

Stacks, masts, samson posts, and other structures, may cause a reduction in the intensity of the radar beam beyond these obstructions, especially if they are close to the radar antenna. If the angle at the antenna subtended by the obstruction is more than a few degrees, the reduction of the intensity of the radar beam beyond the obstruction may produce a blind sector. Less reduction in the intensity of the beam beyond the obstructions may produce shadow sectors. Within a shadow sector, small targets at close range may not be detected, while larger targets at much greater ranges will appear.

Spoking appears on the PPI as a number of spokes or radial lines. Spoking is easily distinguished from interference effects because the lines are straight on all range-scale settings, and are lines rather than a series of dots.

The spokes may appear all around the PPI, or they may be confined to a sector. If spoking is confined to a narrow sector, the effect can be distinguished from a Ramark signal of similar appearance through observation of the steady relative bearing

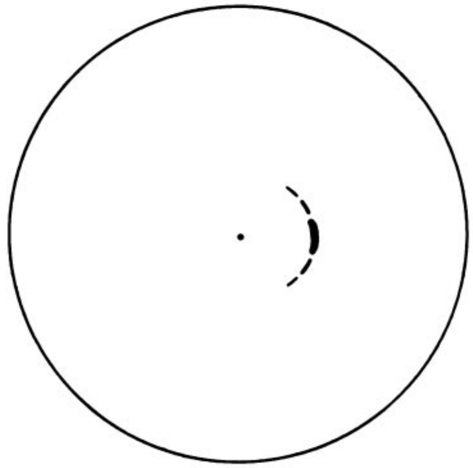


Figure 1307b. Side-lobe effects.

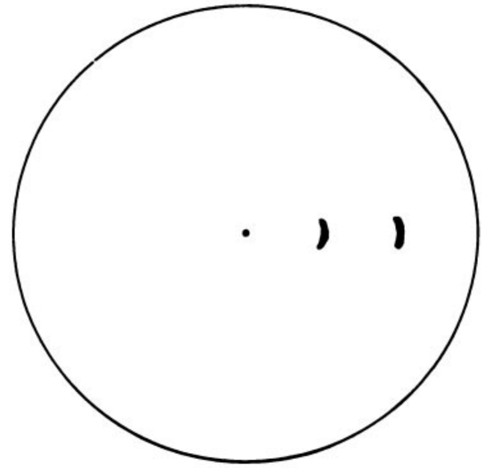


Figure 1307c. Multiple echoes.

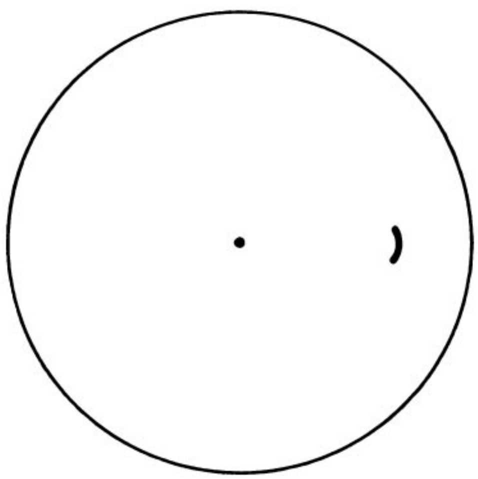


Figure 1307d. Second-trace echo on 12-mile range scale.

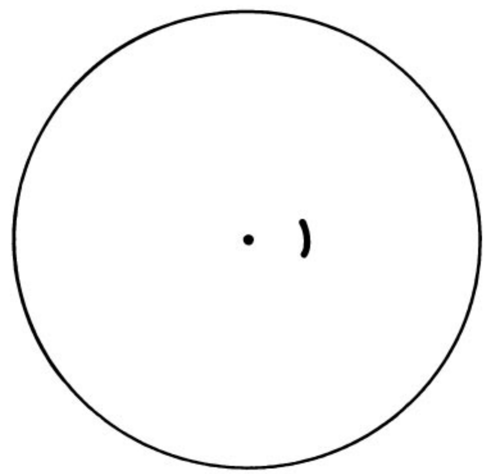


Figure 1307e. Position of second-trace echo on 12-mile range scale after changing PRR.

Figure 1307f

of the spoke in a situation where the bearing of the Ramark signal should change. Spoking indicates a need for maintenance or adjustment.

The PPI display may appear as normal sectors alternating with dark sectors. This is usually due to the automatic frequency control being out of adjustment.

The appearance of serrated range rings indicates a need for maintenance.

After the radar set has been turned on, the display may not spread immediately to the whole of the PPI because of static electricity inside the CRT. Usually, the static electricity effect, which produces a distorted PPI display, lasts no longer than a few minutes.

Hour-glass effect appears as either a constriction or expansion of the display near the center of the PPI. The expansion effect is similar in appearance to the expanded center display. This effect, which can be caused by a nonlinear time base or the sweep not starting on the indicator at the same instant as the transmission of the pulse, is most apparent when in narrow rivers or close to shore.

The echo from an overhead power cable appears on the PPI as a single echo always at right angles to the line of the cable. If this phenomenon is not recognized, the echo can be wrongly identified as the echo from a ship on a steady bearing. Avoiding action results in the echo remaining on a constant bearing and moving to the same side of the channel as the ship altering course. This phenomenon is particularly apparent for the power cable spanning the Straits of Messina.

1308. Aids To Radar Navigation

Radar navigation aids help identify radar targets and increase echo signal strength from otherwise poor radar targets.

Buoys are particularly poor radar targets. Weak, fluctuating echoes received from these targets are easily lost in the sea clutter. To aid in the detection of these targets, **radar**

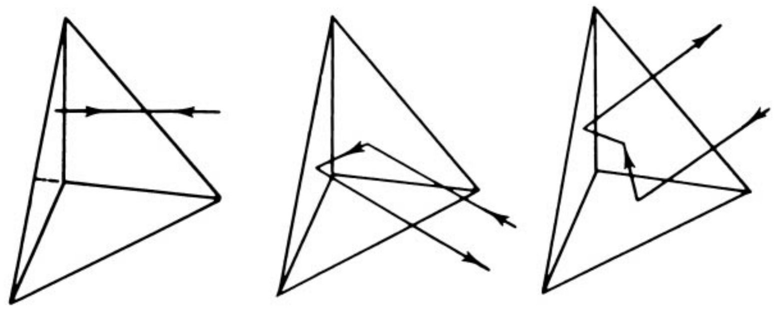


Figure 1308a. Corner reflectors.

reflectors, designated corner reflectors, may be used. These reflectors may be mounted on the tops of buoys. Additionally, the body of the buoy may be shaped as a reflector.

Each corner reflector, shown in Figure 1308a, consists of three mutually perpendicular flat metal surfaces. A radar wave striking any of the metal surfaces or plates will be reflected back in the direction of its source. Maximum energy will be reflected back to the antenna if the axis of the radar beam makes equal angles with all the metal surfaces. Frequently, corner reflectors are assembled in clusters to maximize the reflected signal.

Although radar reflectors are used to obtain stronger echoes from radar targets, other means are required for more positive identification of radar targets. **Radar beacons** are transmitters operating in the marine radar frequency band, which produce distinctive indications on the radarscopes of ships within range of these beacons. There are two general classes of these beacons: **racons**, which provide both bearing and range information to the target, and **ramarks** which provide bearing information only. However, if the ramark installation is detected as an echo on the radarscope, the range will be available also.

A racon is a radar transponder which emits a characteristic signal when triggered by a ship's radar. The signal may be emitted on the same frequency as that of the triggering radar, in which case it is superimposed on the ship's radar display automatically. The signal may be emitted on a separate frequency, in which case to receive the signal the ship's radar receiver must be tuned to the beacon frequency, or a special receiver must be used. In either case, the PPI will be blank except for the beacon signal. However, the only racons in service are "in band" beacons which transmit in one of the marine radar bands, usually only the 3-centimeter band.

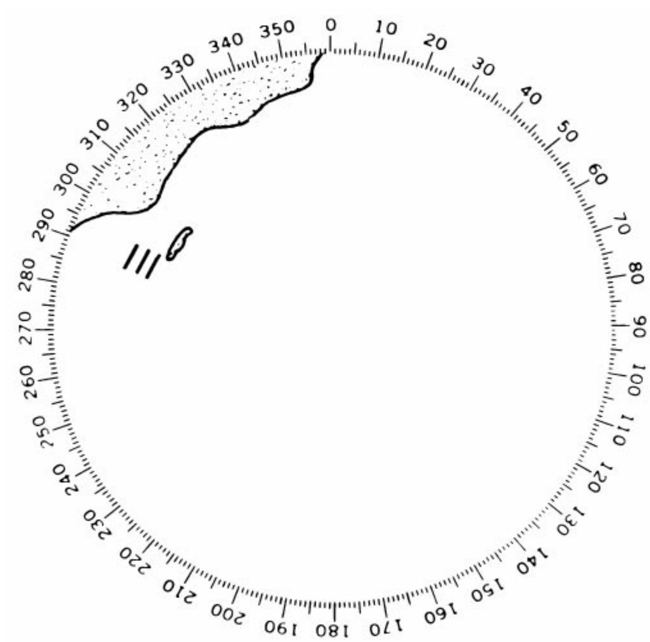


Figure 1308b. Coded racon signal.

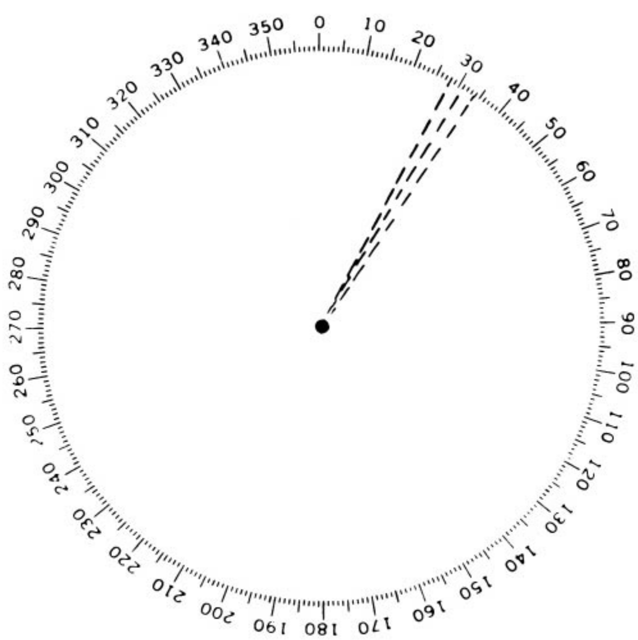


Figure 1308c. Ramark signal appearing as a broken radial line.

The racon signal appears on the PPI as a radial line originating at a point just beyond the position of the radar beacon, or as a Morse code signal (Figure 1308b) displayed radially from just beyond the beacon.

A ramark is a radar beacon which transmits either continuously or at intervals. The latter method of transmission is used so that the PPI can be inspected without any clutter introduced by the ramark signal on the scope. The ramark signal as it appears on the PPI is a radial line from the center. The radial line may be a continuous narrow line, a broken line (Figure 1308c), a series of dots, or a series of dots and dashes.

RADAR PILOTING

1309. Introduction

When navigating in restricted waters, a mariner most often relies on visual piloting to provide the accuracy required to ensure ship safety. Visual piloting, however, requires clear weather; often, mariners must navigate through fog. When conditions render visual piloting impossible and a vessel is not equipped with DGPS, radar navigation provides a method of fixing a vessel's position with sufficient accuracy to allow safe passage. See Chapter 8 for a detailed discussion of integrating radar into a piloting procedure.

1310. Fixing Position By Two Or More Simultaneous Ranges

The most accurate radar fixes result from measuring and plotting ranges to two or more objects. Measure objects directly ahead or astern first; measure objects closest to the beam last. This procedure is the opposite to that recommended for taking visual bearings, where objects closest to the beam are measured first; however, both recommendations rest on the same principle. When measuring objects to determine a line of position, measure first those which have the greatest rate of change in the quantity being measured; measure last those which have the least rate of change in that quantity. This minimizes measurement time delay errors. Since the range of those objects directly ahead or astern of the ship changes more rapidly than those objects located abeam, measure objects ahead or astern first.

Record the ranges to the navigation aids used and lay the resulting range arcs down on the chart. Theoretically, these lines of position should intersect at a point coincident with the ship's position at the time of the fix. However, the inherent inaccuracy of the radar coupled with the relatively large scale of most piloting charts usually precludes such a point fix. In this case, the navigator must carefully interpret the resulting fix. Check the echo sounder with the charted depth where the fix lies. If both soundings consistently correlate, that is an indication that the fixes are accurate. If there is disparity in the sounding data, then that is an indication that either the radar ranges were inaccurate or that the piloting party has misplotted them.

This practice of checking sounding data with each fix cannot be overemphasized. Though verifying soundings is always a good practice in all navigation scenarios, its importance increases tremendously when piloting using only radar. Assuming proper operation of the fathometer, soundings give the navigator invaluable information on the reliability of his fixes. When a disparity exists between the charted depth at the fix and the recorded sounding, the navigator should assume that the disparity has been caused by fix inaccuracy. This is especially true if the fathometer shows the ship heading into water shallower than that anticipated. When there is a consistent disparity between charted and fathometer sounding data, the navigator should assume that he does not know the ship's position with sufficient accuracy to proceed safely. The ship should be slowed or stopped until the navigator is confident that he can continue his passage safely.

1311. Fixing Position By A Range And Bearing To One Object

Visual piloting requires bearings from at least two objects; radar, with its ability to determine both bearing and range from one object, allows the navigator to obtain a fix where only a single navigation aid is available. An example of using radar in this fashion occurs in approaching a harbor whose entrance is marked with a single, prominent light such as Chesapeake Light at the entrance of the Chesapeake Bay. Well beyond the range of any land-based visual navigation aid, and beyond the visual range of the light itself, a shipboard radar can detect the light and provide bearings and ranges for the ship's piloting party.

This methodology is limited by the inherent inaccuracy associated with radar bearings; typically, a radar bearing is accurate to within 5° of the true bearing. Therefore, the navigator must carefully evaluate the resulting position, checking it particularly with the sounding obtained from the bottom sounder. If a visual bearing is available from the object, use that bearing instead of the radar bearing when laying down the fix. This illustrates the basic concept discussed above: radar ranges are inherently more accurate than radar bearings.

Prior to using this single object method, the navigator must ensure that he has correctly identified the object from which the bearing and range are to be taken. Using only one navigation aid for both lines of position can lead to disaster if the navigation aid is not properly identified.

1312. Fixing Position With Tangent Bearings And A Range

This method combines bearings tangent to an object with a range measurement from some point on that object. The object must be large enough to provide sufficient bearing spread between the tangent bearings; often an island is used. Identify some prominent feature of the object that is displayed on both the chart and the radar display. Take a range measurement from that feature and plot it on the chart. Then determine the tangent bearings to the island and plot them on the chart.

1313. Fixing Position By Bearings To Two Or More Objects

The inherent inaccuracy of radar bearings discussed above makes this method less accurate than fixing position by radar range. Use this method to plot a position quickly on the chart when approaching restricted waters to obtain an approximate ship's position for evaluating radar targets to use for range measurements. Speed is the advantage of this method, as the plotter can lay bearings down more quickly than ranges on the chart. Unless no more accurate method is available, do not use this method while piloting in restricted waters.

1314. Fischer Plotting

In Fischer plotting, the navigator adjusts the scale of the radar to match the scale of the chart in use. He then overlays the PPI screen with a clear surface such as Plexiglas and traces the shape of land and location of navigation aids from the radar scope onto the Plexiglas. He then transfers the surface from the radar scope to the chart. He matches the chart's features with the features on the radar by adjusting the tracings on the Plexiglas to match the charts features. Once obtaining the best fit, he marks the ship's position as the center of the Plexiglas cover.

RASTER RADARS

1315. Basic Description

Conventional PPI-display radars use a **Cathode Ray Tube (CRT)** to direct an electron beam at a screen coated with phosphorus. The phosphorus glows when illuminated by an electron beam. Internal circuitry forms the beam such that a "sweep" is indicated on the face of the PPI. This sweep is timed to coincide with the sweep of the radar's antenna. A return echo is added to the sweep signal so that the screen is more brightly illuminated at a point corresponding to the bearing and range of the target that returned the echo.

The raster radar also employs a cathode ray tube; however, the end of the tube upon which the picture is formed is rectangular, not circular as in the PPI display. The raster radar does not produce its picture from a circular sweep; it utilizes a liner scan in which the picture is "drawn," line by line, horizontally across the screen. As the sweep moves across the screen, the electron beam from the CRT illuminates the **pixels** on the screen. A pixel is the smallest area of phosphorus that can be excited to form a picture element.

In order to produce a sufficiently high resolution, some raster radars require over 1 million pixels per screen combined with an update rate of 60 scans per second. Completing the processing for such a large number of pixel elements requires sophisticated, expensive circuitry. One way to lower cost is to slow down the required processing speed. This speed can be lowered to approximately 30 frames per second before the picture develops a noticeable flicker.

Further cost reduction can be gained by using an **interlaced display**. An interlaced display does not draw the entire picture in one pass. On the first pass, it draws every other line; it draws the remaining lines on the second pass. This type of display reduces the number of screens that have to be drawn per unit time by a factor of two; however, if the two pictures are misaligned, the picture will appear to jitter.

Raster radars represent the future of radar technology, and they will be utilized in the integrated bridge systems discussed in Chapter 14.

CHAPTER 14

ECDIS AND THE INTEGRATED BRIDGE

INTRODUCTION

1400. Operating Concept

Bridge watch officers have three main duties:

Navigation

- Watch officers process navigation information from several different sources. They take fix positions from satellite and hyperbolic receivers. They measure bearing lines and radar ranges to suitable NAVAIDS. They then plot this information on a paper chart.

- After plotting the information on a chart, watch officers evaluate the navigation picture. They determine if the ship's present position is a safe one. They project the ship's position ahead and plan for future contingencies. The evaluation step is the most important step in the navigation process. Properly executing this step is a function of the watch officer's skill and how well the ship's actual navigation situation is represented on the chart. That representation, in turn, is a function of both plotter and sensor accuracy.

Collision Avoidance

- Watch officers evaluate the contact situation and calculate the closest points of approach (CPA's) for various contacts.

- Watch officers maneuver in accordance with the Rules of the Road to avoid close CPA's and collisions.

Ship Management

- Watch officers conduct evolutions that are part of an individual ship's routine.

The integrated bridge is designed to reduce the time spent on navigation by eliminating manual data processing and providing the navigator with a display which aids him in quickly evaluating the navigation picture.

Preliminary studies seem to indicate that time spent on navigation as a percentage of total watch officer duties drops significantly when using the integrated bridge. This does not necessarily lower the overall watch officer workload, but it does increase the percentage of time he can devote to ship management and collision avoidance.

THE INTEGRATED BRIDGE

1401. System Components

The term "integrated bridge" encompasses several possible combinations of equipment and software designed specifically for each individual vessel's needs. Therefore, each integrated bridge system is different. This section introduces, in general terms, the major equipment likely to be found in an integrated bridge system.

• **Computer Processor and Network:** This subsystem controls the processing of information from the ship's navigation sensors and the flow of information between various system components. It takes inputs from the vessel's navigation sensors. Electronic positioning information, contact information from radar, and gyro compass outputs, for example, can be integrated with the electronic chart to present the complete navigation and tactical picture to the conning officer. The system's computer network processes the positioning information and controls the integrated bridge system's display and control functions.

• **Chart Data Base:** At the heart of any integrated bridge system lies an electronic chart. An electronic chart system meeting International Maritime Organization (IMO) specifications for complying with chart carrying requirements is an **Electronic Chart Display and Information System (ECDIS)**. All other electronic charts are known as **Electronic Chart Systems (ECS)**. Following sections discuss the differences between these two types of electronic charts.

An integrated bridge system may receive electronic chart data from the system manufacturer or from the appropriate government agency. The mariner can also digitize an existing paper chart if the system manufacturer provides a digitizer. Electronic charts can differentiate between and

display different types of data far better than conventional charts. Paper charts are usually limited to four colors, and they display all their data continuously. An electronic chart can display several colors, and it can display only the data the user needs. If the electronic chart is part of an ECDIS, however, it must always display the minmum data required by IMO/IHO. The database for a typical civilian electronic chart contains layers consisting of hydrography, aids to navigation, obstructions, port facilities, shoreline, regulatory boundaries and certain topographic features. Other layers such as communication networks, power grids, detailed bathymetry, and radar reflectivity can also be made available. This allows the user to customize his chart according to his particular needs, something a paper chart cannot do.

• **System Display:** This unit displays the ship's position on an electronic chart and provides information on sensor status and ship's control systems. It displays heading data and ship's speed. It provides a station where the operator can input warning parameters such as minimum depth under the keel or maximum cross track error. It plots the ship's position and its position in relation to a predetermined track.

There are two possible modes of display, **relative** and **true**. In the relative mode the ship remains fixed in the center of the screen and the chart moves past it. This requires a lot of computer power, as all the screen data must be updated and re-drawn at each fix. In true mode, the chart remains fixed and the ship moves across it. The operator always has the choice of the north-up display. On some equipment, the operator can select the course-up display as well. Each time the ship approaches the edge of the display, the screen will re-draw with the ship centered or at the opposite edge.

A separate monitor, or a window in the navigation monitor, can be used for display of alpha-numeric data such as course, speed, and cross-track error. It can also be used to display small scale charts of the area being navigated, or to look at other areas while the main display shows the ship's current situation.

• **Planning Station:** The navigator does his voyage planning at this station. He calculates great circle courses, planned tracks, and waypoints. The navigator digitizes his charts, if required, at this planning station.

• **Control System:** Some integrated bridges provide a system that automatically adjusts course and speed to follow a planned track. If the system is equipped with this feature, the navigation process is reduced to monitoring system response and providing operator action when required by either a changing tactical situation or a system casualty.

• **Radar:** Radar for navigation and collision avoidance is included in the integrated bridge. Since both the chart and the radar process their data digitally, data transfer between the two is possible. The "picture" from either one can be imposed on top of the picture of the other. This allows the navigator to see an integrated navigation and tactical display and to avoid both navigation hazards and interfering contacts.

ELECTRONIC CHART DISPLAY AND INFORMATION SYSTEM

The unqualified use of the electronic chart in the integrated bridge depends on the legal status of the electronic chart system in use. The IMO has defined the Electronic Chart Display and Information System as the integrated bridge system that complies with the up-to-date chart carrying requirements of international law. The Electronic Nautical Chart (ENC) is the ship's electronic chart data base used in an ECDIS system. The ENC is a subset of the Electronic Chart Database (ECDB), the digital chart database maintained by the national hydrographic authority.

ECDIS standards are still under development. This section will discuss some basic ECDIS design criteria.

1402. Digital Chart Data Formats

One question in the development of ECDIS has been whether the nautical chart should be digitized in **raster** or **vector** format.

Raster chart data is a digitized "picture" of a chart. All data is in one layer and one format. The video display simply reproduces the picture from its digitized data file. With raster data, it is difficult to change individual elements of the chart since they are not separated in the data file. Raster data files tend to be large, since a data point must be entered for every picture element (pixel) on the chart.

Vector chart data is organized into many separate files. It contains graphics programs to produce certain symbols, lines, area colors, and other chart elements. The programmer can change individual elements in the file and tag elements with additional data. Vector files are smaller and more versatile than raster files of the same area. The navigator can selectively display vector data, adjusting the display according to his needs. Current IMO/IHO standards for ECDIS recognize only the vector format as adequate.

Whether a digital chart system uses a raster or vector data base, any change to that data base must come only from the hydrographic office (HO) that produced the ENC. Corrections from other sources affecting the data base should be applied only as an overlay to the official data base. This protects the integrity of the official data base.

1403. Digital Chart Data Transfer

The IMO, in its performance standards for ECDIS, has

mandated that individual national hydrographic offices will supply official ENC data for ECDIS use. A preliminary data transfer standard, known as **DX 90**, has been proposed within the IHO; IHO is debating the utility of this standard. Regardless of the transfer standard recommended, each national hydrographic office that produces a data base will decide what transfer standard it will use.

To ensure the reliability of the data, the ECDIS must not allow data from an unofficial source to erase, overwrite, or modify HO supplied data.

1404. ECDIS Warnings And Alarms

Since the ECDIS is a "smart" system which combines several different functions into one computerized system, it is possible to program it to sound alarms or display warnings when certain parameters are met or exceeded. This helps the navigator to monitor close navigation hazards. IMO standards require that certain alarms be available on the ECDIS. Among these are:

1. Deviating from a planned route.
2. Chart on a different geodetic datum from the positioning system.
3. Approach to waypoints and other critical points.
4. Exceeding cross-track limits.
5. Chart data displayed overscale (larger scale than originally digitized).
6. Larger scale chart available.
7. Failure of the positioning system.
8. Vessel crossing safety contour.
9. System malfunction or failure.

Alarms consist of audible and visible warnings. The navigator may determine some setpoints. For example, he may designate a safety depth contour or set a maximum allowed cross-track error. Operational details vary from one system to another, but all ECDIS will have the basic alarm capabilities noted. The navigator is responsible for becoming familiar with the system aboard his own ship and using it effectively.

1405. ECDIS Units

The following units of measure will appear on the ECDIS chart display:

- **Position:** Latitude and Longitude will be shown in degrees, minutes, and decimal minutes, normally based on WGS-84 datum.

- **Depth:** Depth will be indicated in meters and decimeters. Fathoms and feet may be used as an interim measure only:
  - when existing chart udata is held in those units only,
  - when there is an urgent need for an ENC of the applicable area, and
  - time does not allow for an immediate conversion of the English units to their metric equivalents.

- **Height:** Meters (preferred) or feet.

- **Distance:** Nautical miles and decimal miles, or meters.

- **Speed:** Knots and decimal knots.

1406. ECDIS Priority Layers

ECDIS requires data layers to establish a priority of data displayed. The minimum number of information categories required and their relative priority from the highest to lowest priority, are listed below:

- ECDIS Warnings and Messages.
- Hydrographic Office Data.
- Notice to Mariners Information.
- Hydrographic Office Cautions.
- Hydrographic Office Color-Fill Area Data.
- Hydrographic Office On Demand Data.
- Radar Information.
- User's Data.
- Manufacturer's Data.
- User's Color-Fill Area Data.
- Manufacturer's Color-Fill Area Data.

IMO standards for ECDIS will require that the operator be able to deselect the radar picture from the chart with minimum operator action for fast "uncluttering" of the chart presentation.

1407. ECDIS Calculation Requirements

As a minimum, an ECDIS system must be able to perform the following calculations:

- Geographical coordinates to display coordinates, and display coordinates to geographical coordinates.

- Transformation from local datum to WGS-84.

- True distance and azimuth between two geographical positions.

• Geographic position from a known position given distance and azimuth.

• Projection calculations such as great circle and rhumb line courses and distances.

ELECTRONIC CHART SYSTEMS

1408. ECS And ECDIS

Electronic Chart Systems (ECS) are those digital chart display systems that do not meet the IMO requirements for ECDIS. Until an ECDIS standard is approved and a particular ECS meets that standard, no ECS can be classified as an ECDIS. The practical consequence of this distinction is that an ECS cannot be used to replace a paper chart.

Legal requirements notwithstanding, several companies are producing very sophisticated integrated bridge systems based on electronic chart systems. These integrated bridges combine accurate electronic positioning sensors with electronic chart presentations to produce a video representation of a chart which displays and updates the ship's charted position at frequent intervals. Electronic charts can also display tracklines, cross-track error, and other operational data. These systems have the potential to integrate radar systems and control systems to create a fully integrated bridge.

The uncertainty surrounding the final ECDIS standard has not lessened the marine community's demand to exploit the potential of this revolutionary technology.

One consequence of this demand has been that some national hydrographic offices are producing official digital raster charts for use in electronic charting systems. In addition, a number of commercial companies have been licensed to digitize the paper charts of various national hydrographic offices. However, these are not the data bases envisioned by the IMO standard.

Remember that ECDIS is a *system*. The electronic chart data base is only a subset of this system. Therefore, even though electronic charts come from a national hydrographic office or from official charts, the integrated bridge system in which the chart is used may not meet the ECDIS *system* requirements.

NAVIGATION SENSOR SYSTEM INTERFACE (NAVSSI)

1409. System Description

DMA's Vector Product Format (VPF) Digital Nautical Charts (DNC's) are used in conjunction with the Navy's version of the integrated bridge: the **Navigation Sensor System Interface (NAVSSI)**. NAVSSI is being developed to fulfill three important functions:

- Navigation Safety: NAVSSI distributes real time navigation data to the navigation team members to ensure navigation safety.
- Weapons System Support: NAVSSI provides guidance initialization for use by weapons systems.
- Battlegroup Planning: NAVSSI provides a worksation for battlegroup planning.

The navigation function of NAVSSI, therefore, is only one of several functions accomplished by the system. The navigational portion of NAVSSI is being designed to comply with the IMO/IHO ECDIS standards for content and function.

The heart of NAVSSI is the Real Time Subsystem (RTS). The RTS receives, processes and distributes navigational data to the navigation display, weapons systems, and other networked vessels. This ensures that all elements of a battle group have the same navigational picture. Inputs come from GPS, Loran, inertial navigation systems, gyrocompass, and speed log. The bridge display consists of a monitor and control panel, while the RTS is mounted below decks. ENC's are contained in the **Display and Control Subsystem (DCS)** typically mounted in the chartroom with a monitor on the bridge. This is unlike many current commercial systems which have all hardware and software in a single unit on the bridge. A separate NAVSSI software package supports operator interface, waypoint capability, collision and grounding avoidance features, and other aspects of an ECDIS.

Figure 1409 illustrates a basic block diagram of the NAVSSI system. The RTS takes inputs from the inertial navigators (WSN-5's), the GPS PPS (WRN-6), the gyro compass, the EM Log, and the SRN-25. The SRN-25 outputs GPS SPS, Transit SATNAV, and Omega positions. The RTS distributes navigation information to the various tactical applications requiring navigation input, and it communicates via a fiber optic network with the DCS. The DCS exchanges information with the Navigator's Workstation.

1410. The Digital Nautical Chart

NAVSSI uses the **Digital Nautical Chart (DNC)** as its chart database. The DNC is in Vector Product Format and is based on the contents of the traditional paper harbor, approach, and coastal charts produced by DMA and NOS.

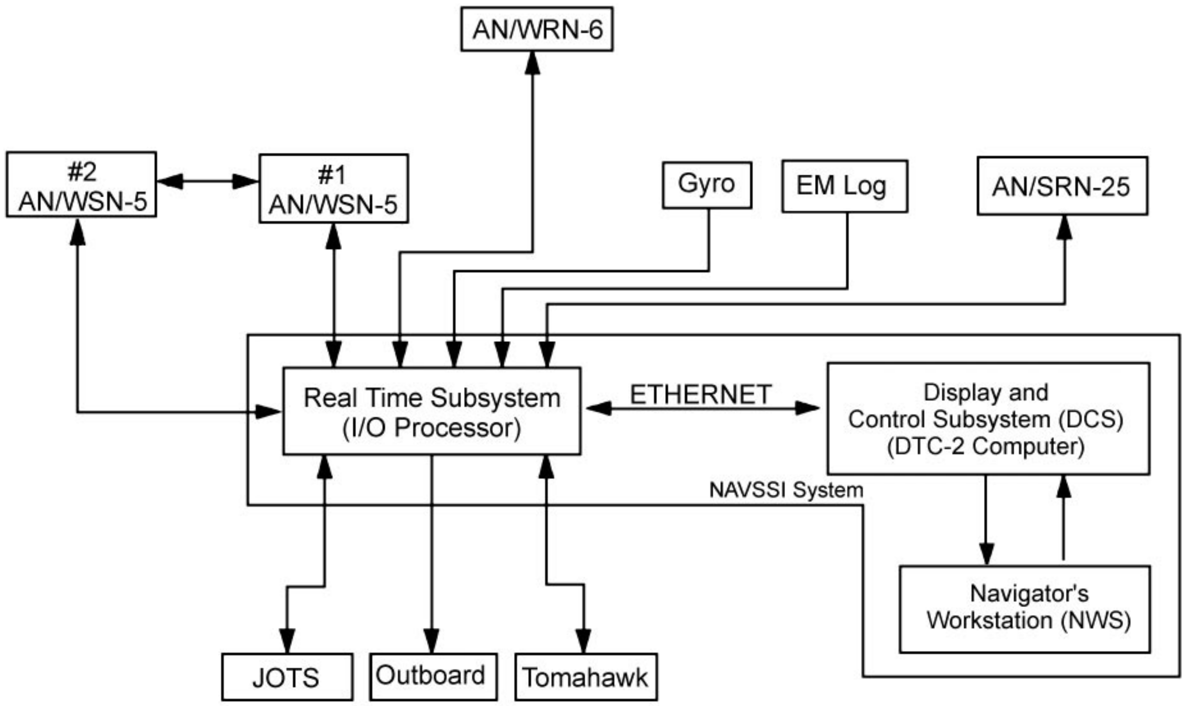


Figure 1409. Block diagram of NAVSSI.

Horizontal datum is WGS 84 (NAD 83 in the U. S. is equivalent). There are three vertical datums. Topographic features are referenced to Mean Sea Level, and the shore line is referenced to Mean High Water. Hydrography is referenced to a low water level suitable for the region. All measurements are metric.

DNC data is layered together into 12 related feature classes:

- Cultural Landmarks
- Earth Cover
- Inland Waterways
- Relief
- Landcover
- Port Facilities
- Aids to Navigation
- Obstructions
- Hydrography
- Environment
- Maritime Limiting Lines (channels, demarcation lines, anchorages, etc.)
- Data Quality

Content is generally the same as on a paper chart. The data is stored in **libraries**; each library represents a different level of detail. The libraries are then stored on CD-ROM and organized as tiles according to the **World Geodetic Reference System (GEOREF)** tiling scheme. Tile sizes are 15' X 15' for harbor charts, 30' X 30' for approach charts, and 3° X 3° for general charts. The data now contained on as many as 4000 conventional charts will eventually be contained on as few as 30 CD's.

1411. Correcting The Digital Nautical Chart

There are currently three proposed methods for correcting the DNC data base: Interactive Entry, Semi-Automatic Entry, and Fully Automatic Entry.

Interactive Entry: This method requires the interactive application of the textual Notice to Mariners. The operator determines the corrections from the Notice. Then, using a toolkit, he selects the symbol appropriate to the correction required, identifies the location of the symbol, and adds the appropriate textual information identifying the nature of the correction. This method of correction is labor intensive and subject to operator error. It also clutters the screen display because it can be applied only as an overlay to the ENC data.

Semi-Automatic Entry: This method requires the operator to enter the correction data furnished in correct digital format by the originating hydrographic office into the system via electronic medium (a modem or floppy disc, for example). The ECDIS then processes these corrections automatically and displays an updated chart with the changed data indistinguishable from the remaining original data base.

Fully Automatic Entry: The fully automatic method of correction entry allows for a direct telecommunications link to receive the official digital update and input it into the ECDIS. This process is completely independent of any operator interface. Internal ECDIS processing is the same as that for semi-automatic updating of the data base.

CONCLUSION

The emergence of extremely accurate electronic positioning systems coupled with the technology to produce an electronic chart is effecting a revolution in navigation. When fully mature, this technology will replace the paper charts and plotting instruments used by navigators since the beginning of sea exploration. There are several hurdles to overcome in the process of full replacement of paper charts, some legal, some bureaucratic, and some technical. Until those hurdles are overcome, electronic charting will be in a transitional state, useful as a backup to traditional techniques, but insufficient to replace them. How this transition period will play out and the final form of the internationally recognized ECDIS system are subjects for the next edition of *The American Practical Navigator*.